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Studies of Emissions from Gasoline-Powered Vehicles Above 6,000-lb Gross Vehicle Weight

Southwest Research Inst, San Antonio, Tex

Prepared for
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by
Clifford D. Tyree
Karl J. Springer

FINAL REPORT

Prepared for

Procedures Development Branch
Division of Motor Vehicle Pollution Control
National Air Pollution Control Administration
Contract No. PH 86-67-78
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ABSTRACT

Continued studies of heavy-duty gasoline-powered vehicle emissions (above 6000-lb gross vehicle weight), sponsored by the National Air Pollution Control Administration, Department of Health, Education, and Welfare, are described. Featured in this report are comparisons of road route hydrocarbon, carbon monoxide, and nitric oxide emissions to chassis dynamometer (Federal 9-mode constant speed cycle) for gas trucks of various sizes and makes. Using a constant volume sampler with results expressed in grams per pound of fuel, the current Federal cycle was subjected to a number of modifications to investigate their effect on the road--9-mode cycle relationship. Limited studies with two trucks included comparison of 9-mode cycle results with the engine chassis and stationary operated. Also explored were the potentialities of operating an engine at its peak torque rpm at a variety of power modes. Continued study of alternative dynamometer procedures, sampling, analysis, and methods of expressing gasoline truck emissions is recommended.

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I. INTRODUCTION

According to the latest statistical information[1]*, all trucks comprise about 16.9 percent of the total vehicles (16,194,000 vehicles) and burn approximately 27.6 percent of the gasoline consumed in the United States. From sales data[1], approximately 15 percent of the 15,194,000 vehicles are trucks and buses above a 6000-lb gross vehicle weight (GVW). This estimate includes some diesel vehicles. A great deal of emissions data has been published on automobiles, but there is a significant lack of published emissions data from trucks. Past efforts by Southwest Research Institute for the National Air Pollution Control Administration (NAPCA) included acquisition of baseline emissions data from 180 gasoline and LPG fueled spark-ignited engine powered trucks and buses using three experimental road-like chassis dynamometer procedures. To acquire the emissions, a special truck version of the NAPCA constant volume sampler was used which permitted expression of contaminants on a mass basis. The results of the survey are contained in the SwRI final report[2] which concluded that the three proposed experimental nonconstant speed cycles were not recommended for use in testing emissions from heavy-duty vehicles powered by spark-ignited engines. The findings of these earlier studies were summarized in AIChE and SAE papers[3, 4] which described the preparations and baseline data results, respectively.

On April 1, 1969, Modification 10 to Contract PH 86-67-72 authorized the continued study of emissions from vehicles above 6000-lb GVW (defined as heavy-duty application) and powered by gasoline-fueled, spark-ignited engines. The planned work phases under this contract modification, known as SwRI project 11-2056-03, were to be handled as two general phases covering developmental and proof testing. After completing the developmental phase and reviewing the data gathered with the project officer, the proof testing phase was replaced with a second development phase.

During the initial development phase, emission data were obtained from six trucks above 6000-GVW. Each vehicle was operated over a road course and the exhaust gas sampled by means of a constant volume sampler (CVS). Road emission data obtained with the CVS system were then compared to CVS emission data obtained from the same vehicle during the Federal 9-mode constant speed[5] procedure using the chassis dynamometer. Several modifications to the Federal procedure were studied.

At the start of the program, it was anticipated that the second phase would involve proof testing of a modified Federal Procedure, obtained during

*Superscript numbers in parentheses refer to List of References at the end of this report.

phase I, on a number of trucks. However, at the conclusion of phase I, a second developmental phase was suggested after reviewing the data with the project officer. This phase differed from the first phase in that an entirely new type of test procedure would be evaluated. This evaluation encompassed the Federal 9-mode procedure conducted on the chassis and stationary dynamometers as well as an additional procedure.

II. OBJECTIVE

The overall objective of the current studies at Southwest Research Institute is to study the emissions from gasoline-powered trucks above 6000-lb GVW. The most advanced emissions sampling and analysis procedures for both field and laboratory operation were used. To establish whether or not the current Federal procedure for heavy duty gasoline engines reflects actual operation of vehicles in traffic, the initial objective was to operate a given number of vehicles and measure their emissions under road and dynamometer laboratory conditions. The alternate chassis dynamometer version of the constant speed procedure established by California[5] and proposed in the January 4, 1968, Federal Register[7] was used to operate the vehicles in the dynamometer laboratory.

The next objective of these developmental studies was to investigate the effect of modifications to the Federal procedure in an attempt to make the dynamometer results agree with the road emissions results. The final objective was to evaluate a new engine test procedure and compare the results obtained from the 9-mode Federal procedure, using the stationary and chassis dynamometer.

III. SAMPLING AND ANALYSIS EQUIPMENT, INSTRUMENTS AND PROCEDURES

Two sampling and analysis systems were used to obtain exhaust emission data during the developmental portion of this project. The most familiar sampling and analysis system, the continuous sampler[5, 6, 7] using the NDIR analytical system, is described first. Modifications to the truck version[8] of the PHS constant volume sampler, which was used to compare the road emissions with dynamometer cycles, are also reviewed.

A. Continuous Sampling and Analysis

This exhaust gas sampling and analysis method (shown right-center of Figure 1) is specified under Federal regulations[5] and is used for testing of spark-ignited, gasoline-fueled vehicles. A component description of the system includes a regulated exhaust gas flow rate through water condenser traps to four rapid and continuous, nondispersive, infrared (NDIR) gas analyzers. The analysis system consists of a carbon monoxide analyzer, 0 to 11 percent CO, a carbon dioxide analyzer, 0 to 16 percent CO_2, and two hydrocarbon analyzers, 0 to 1000 ppm HC and 0 to 10,000 ppm HC as normal (n) hexane (C_6H_{14}). The continuous analysis readout is accomplished almost instantaneously via two dual-pen strip chart recorders. The present system does not include instrumentation for the measurement of various nitrogen oxides (NO_x); however, suitable NDIR instrumentation is available for the measurement of nitric oxide (NO). Shortcomings of the continuous system include momentous data reduction; however, computers are helping to overcome this problem.

B. PHS Constant Volume Sampling System and Description of Modifications

This sampling system is a PHS development using the inherent integrated bag sample technique. The sampler dilutes the total exhaust gas flow with ambient air such that a constant total flow results. The particular sampler used was an enlarged version of the PHS automotive prototype in that the sampling system would handle increased flow at a higher temperature from truck-size engines. This item was prepared during the previous project.[8]

Figure 2 is a schematic of the truck version constant volume sampler modified to obtain samples of exhaust under field operation over the road course as well as in the dynamometer laboratory. The total flow of exhaust gas plus substantial diluent air flows through a "U" shaped, air-to-exhaust shell and tube, stainless steel heat exchanger. This heat exchanger serves as a heat sink for the moving exhaust gases; that is, the rapid exhaust gas

FIGURE 1. STAKE BODY TRUCK UNDER DIESTONE TEST WITH CONTINUOUS AND CONSTANT VOLUME SAMPLERS

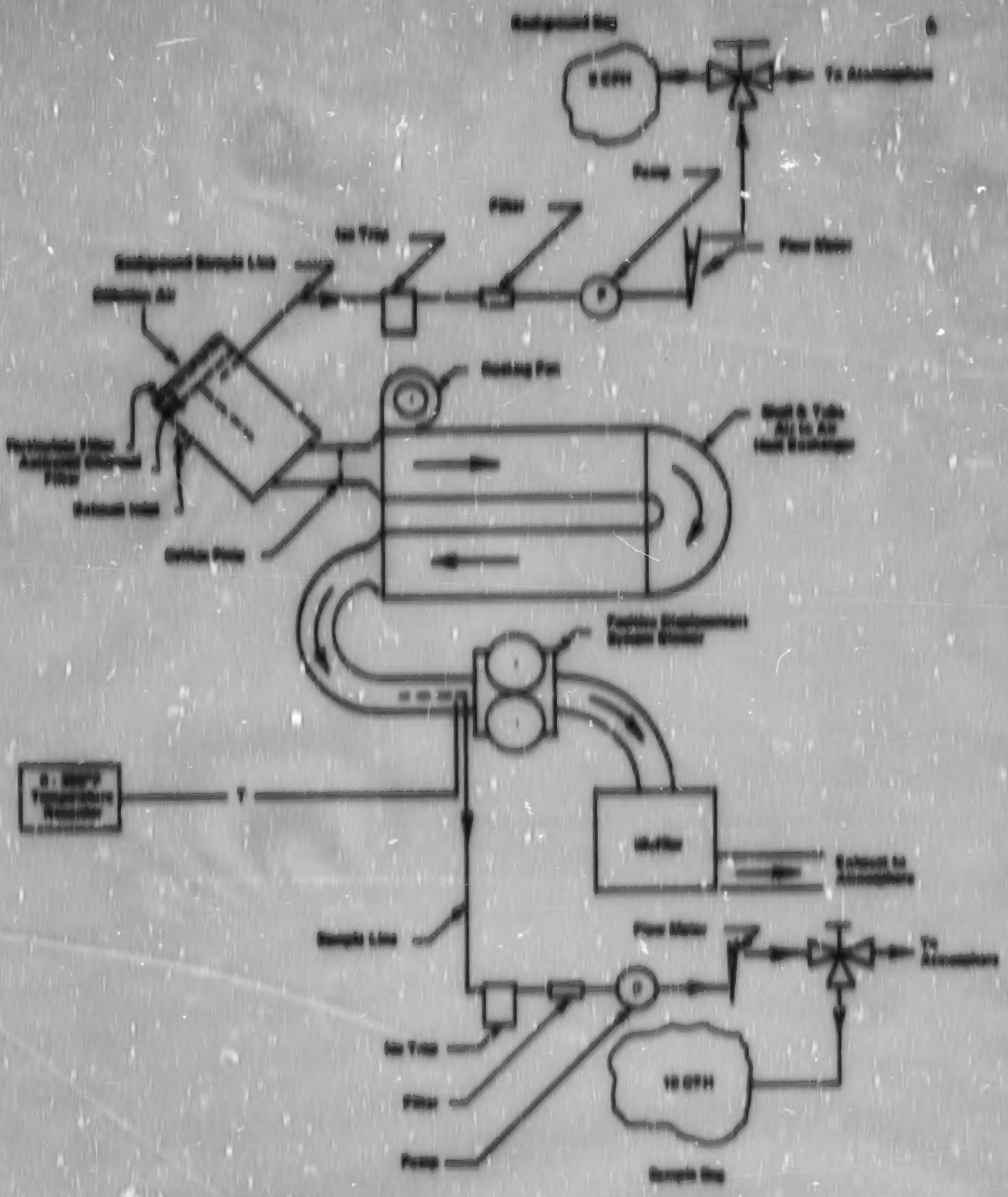

FIGURE 1. SCHEMATIC OF REVISED TRUCK VERSION OF CONSTANT VOLUME SAMPLER

temperature changes are reduced to a minimum so the mode changes are not seen at the inlet to the blower. The removal of the diluent sample by the 1/4-in. probe is just upstream of the main system rotary positive displacement pump. A constant flow of 10 CFM is extracted from the main diluent sample line through a diaphragm sample pump. This "split off" of representative sample is deposited in a Tedlar® bag during the test procedure. All portions of the sampling system in contact with the diluent exhaust sample are fabricated of stainless steel or Teflon®, except for the Viton-A pump diaphragm.

Changes made to the sampler for field operation included addition of a 1-in. thick fiberglass filter and an 8.5-in. thick 24 × 24-in. activated charcoal filter to remove particulate and hydrocarbons from the diluent air. The total vehicle exhaust is routed into the plenum chamber which houses the filters prior to the usual mixing orifice and heat exchanger. The side entry of the vehicle exhaust into the relatively slow moving diluent within the plenum chamber resulted in no measurable interference in normal vehicle operation. This was checked by both exhaust backpressure, performance such as idle speed, and by exhaust emissions with and without the exhaust directed to the sampler at a variety of engine speeds and loads. A small sample, 5 CFH, of filtered diluent air is obtained continuously during operation by means of a diaphragm pump and placed into a 2 × 3-ft Tedlar® background air sample bag. As shown in Figure 2, the diluent air sample is routed through an ice trap to remove excess moisture, a fiberglass particulate filter and a glass rotameter to monitor flow rate which is adjusted by a needle valve at the inlet to the rotameter.

Previous experience indicated that the large heat exchanger cooling air blower could be replaced by a smaller unit. Also, the 4-CFM sample system was replaced by a Dia Pump with Viton-A type diaphragm and operated to obtain 10-CFH of diluted exhaust prior to its entry into the main sample pump. The 10-CFH of diluted exhaust was handled similarly to the background air sample namely through an ice trap, filter, and rotameter. A 2 × 4.5-ft Tedlar® bag was sufficient to contain the sample obtained during about 20 min of operation. A muffler was added to silence the main pump noise to permit operation of the unit on city streets. Changes to the inlet of the system to prefilter the diluent, and to the exhaust to muffle the noise, changed the overall pressure drop across the main system pump necessitating recalibration of the system. The method of calibration was the same as that employed during the original preparation of the sampler.[11] Figure 3 is a plot of the main system flow in SCFM at 69°F and 14.7 psia relative to the inlet temperature of the blower. Both rotameters were checked for accuracy and calibrated using a laboratory wet test meter.

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System Flow - Standard cu ft per minute

Figures 4 through 9 illustrate the constant volume sampler under field and laboratory operation in several test trucks. Figures 4 through 6 are several views of a 10,000-lb-GVW stake body truck prepared for field study and exhaust sampling using the constant volume method. Care was taken to direct the diluted exhaust from the sampler and the exhaust from the trailer mounted 30-kw engine generator away from the samplers air intake, and to locate the sampler intake as high as practical to minimize background contamination in the sampler diluent. The "fifth" wheel, used for vehicle speed measurement, is attached to the rear of the truck, as shown in Figure 4.

Figures 7 and 8 are two views of a tractor-trailer prepared for road emissions acquisition. Note the several large concrete blocks mounted on the trailer for additional weight and the close proximity of the sampler to the vehicle exhaust exit (Figure 7). Figure 9 shows a van body truck under dynamometer test in the laboratory with the constant volume sampler. When operating on the dynamometer, laboratory electrical power was used to operate the sampler equipment. Figures 10 and 11 are close-up views of the modified sampler showing the ice traps and sample bags (Figure 10) and the control panel (Figure 11).

Both sample bags, one containing filtered diluent air and the other containing the diluent air plus vehicle exhaust, were then analyzed using the instruments shown in Figure 12. Nondispersive infrared (NDIR) analyzers were used to measure carbon monoxide (CO), carbon dioxide (CO_2), and nitric oxide (NO), the principal nitrogen oxide in vehicle exhaust. An NDIR was also used to measure hydrocarbons as ppm hexane. Use of this type of instrument for measurement of low concentration hydrocarbons is not as precise as desired due to water vapor interference. A more accurate indication of hydrocarbons is obtained by the hydrogen flame ionization analysis (FIA) instrument shown in Figure 12. Measurement of nitric oxide was made after the sample had been directed through an additional ice water trap particulate filter, and drierite desiccant for removal of the remaining water vapor. This was necessary to eliminate the gross interference of water vapor on NO measurements, even with the latest instrumentation using optically coated filters to minimize this interference. Repeated checks have shown that the particular indicating type of drierite did not alter the concentration (either increase or decrease) of NO in the exhaust.

Large quantities of atmospheric air, even though charcoal filtered, can contain some hydrocarbons, carbon monoxide, and nitrogen oxides; therefore, the background bag of air, taken during the run, must be analyzed. The background concentration is subtracted from the sample concentration to obtain the actual concentration of the exhaust gas.

C. Road Course Description

During a visit by Mr. Bob Olsen, the NAPCA project officer cognizant of the previous heavy-duty gasoline-powered truck work, a road route was

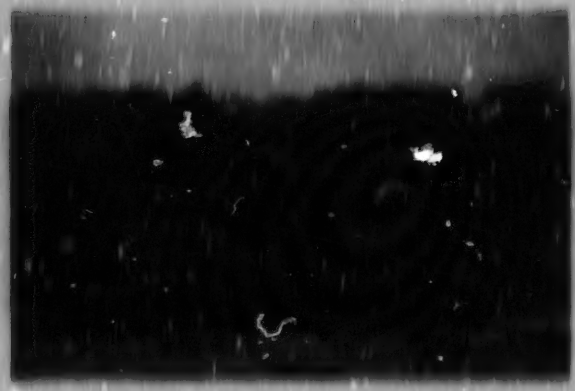

FIGURE 4. STAKE BODY TRUCK PREPARED FOR EXHAUST SAMPLING (Side View)

FIGURE 5. STAKE BODY TRUCK PREPARED FOR EXHAUST SAMPLING (Right Rear View)

FIGURE 6. STAKE BODY TRUCK PREPARED FOR EXHAUST SAMPLING (Left Rear View)

FIGURE 7. TRACTOR-TRAILER TRUCK PREPARED FOR ROAD EMISSIONS ACQUISITION (Curbside View)

FIGURE 8. TRACTOR-TRAILER TRUCK PREPARED FOR ROAD EMISSIONS ACQUISITION (Street Side View)

FIGURE 9. VAN TRUCK UNDER EMISSIONS TEST WITH CONSTANT VOLUME AND CONTINUOUS SAMPLERS

FIGURE 10. STAKE BODY TRUCK WITH CONSTANT VOLUME SAMPLER - DYNAMOMETER TEST

FIGURE 11. MODIFIED CONSTANT VOLUME SAMPLER CONTROL PANEL

FIGURE 12. NON-DISPERSIVE INFRARED, ULTRAVIOLET, AND FLAME IONIZATION ANALYSIS OF CO, CO_2, HYDROCARBONS AND OXIDES OF NITROGEN

agreed upon which included a variety of truck operation typical of city-suburban delivery. This 7.24-mile-long course is shown in Figure 13 and includes both stop and go driving in downtown, residential, and commercial areas as well as cruise operation over a section of the original expressway in San Antonio with a speed limit of 60 mph. Figure 13A is the alternate truck route (6.45 miles) used for the 1968 IHC tractor-trailer unit. This modified route was necessary to keep the larger tractor-trailer on truck routes and out of the narrow streets in the center city portion of the course. The drivers, all experienced truck operators, were asked to drive with the traffic and not exceed the posted speed limit. Above all, they were to drive normally. Figures 14 and 15 show some of the special instrumentation employed to measure selected road operation parameters.

To obtain operating parameters of the truck on the road route, four channels of information were recorded on the two dual pen recorders shown in Figure 14. These parameters were road speed, manifold vacuum, engine rpm, and throttle position. A fifth wheel was used to obtain vehicle speed and a strain gage transducer used for manifold vacuum. An electric tachometer was used for engine rpm and a linear transducer, shown in Figure 15, was used to obtain the throttle position. By attaching a magnetic counter to the fifth wheel, distance between selected points on the road route (see Figure 11) was obtained. A system was installed which enabled the driver to drive the road course and switch to a weighed amount of fuel stored in a 5-gal can (Figure 14) and switch back after completing the run. The fuel was then weighed when the sample bags were returned to the lab from the road route. All fuel burned during the road test, including that consumed in the laboratory, was indolene fuel.

B. Method of Calculation

The data reduction method and the calculation of results for the constant speed procedures using the continuous NDIR cart were as specified in the appropriate Federal Register.[4] The contaminant concentrations measured in the background and sample bags of the constant volume sampler were reduced to a mass basis by a calculation procedure similar to that developed during the previous gasoline truck studies.[5] The procedure is described step by step in Appendix A. A copy of the raw data sheet is included to indicate the simplicity of calculation. As described in the calculation procedure, the emissions from both road and dynamometer are expressed on a grams per pound of fuel burned. Much study was made of alternative methods of expression and, for purposes of indicating emissions, this means was found the most reasonable and foolproof. For comparison of emissions from the same truck, no better method was available.

During some stationary engine tests, observed flywheel horsepower-hour calculations were made for the current 9-mode Federal cycle as follows:

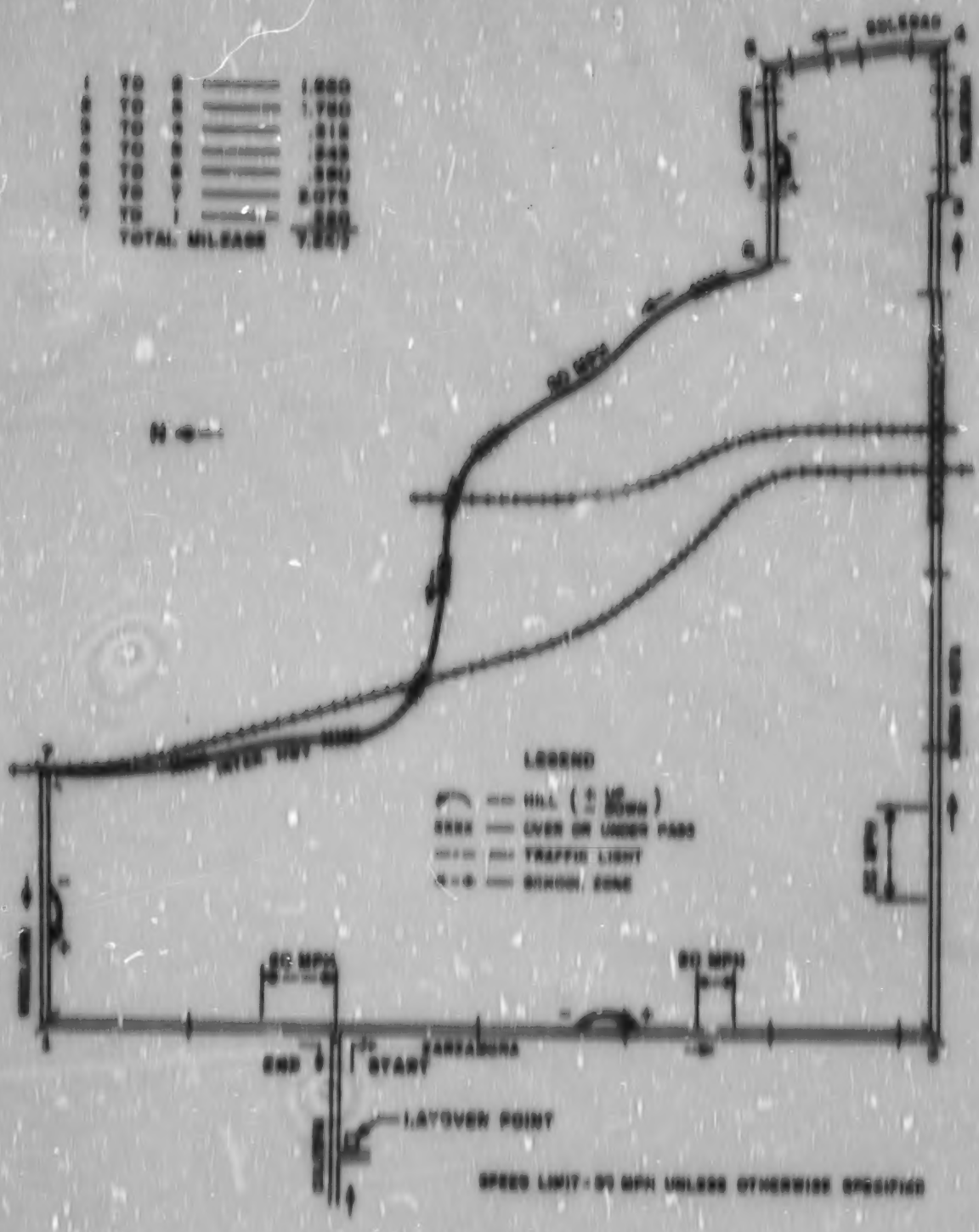

FIGURE 13. SAN ANTONIO HEAVY DUTY GASOLINE TRUCK ROAD ROUTE

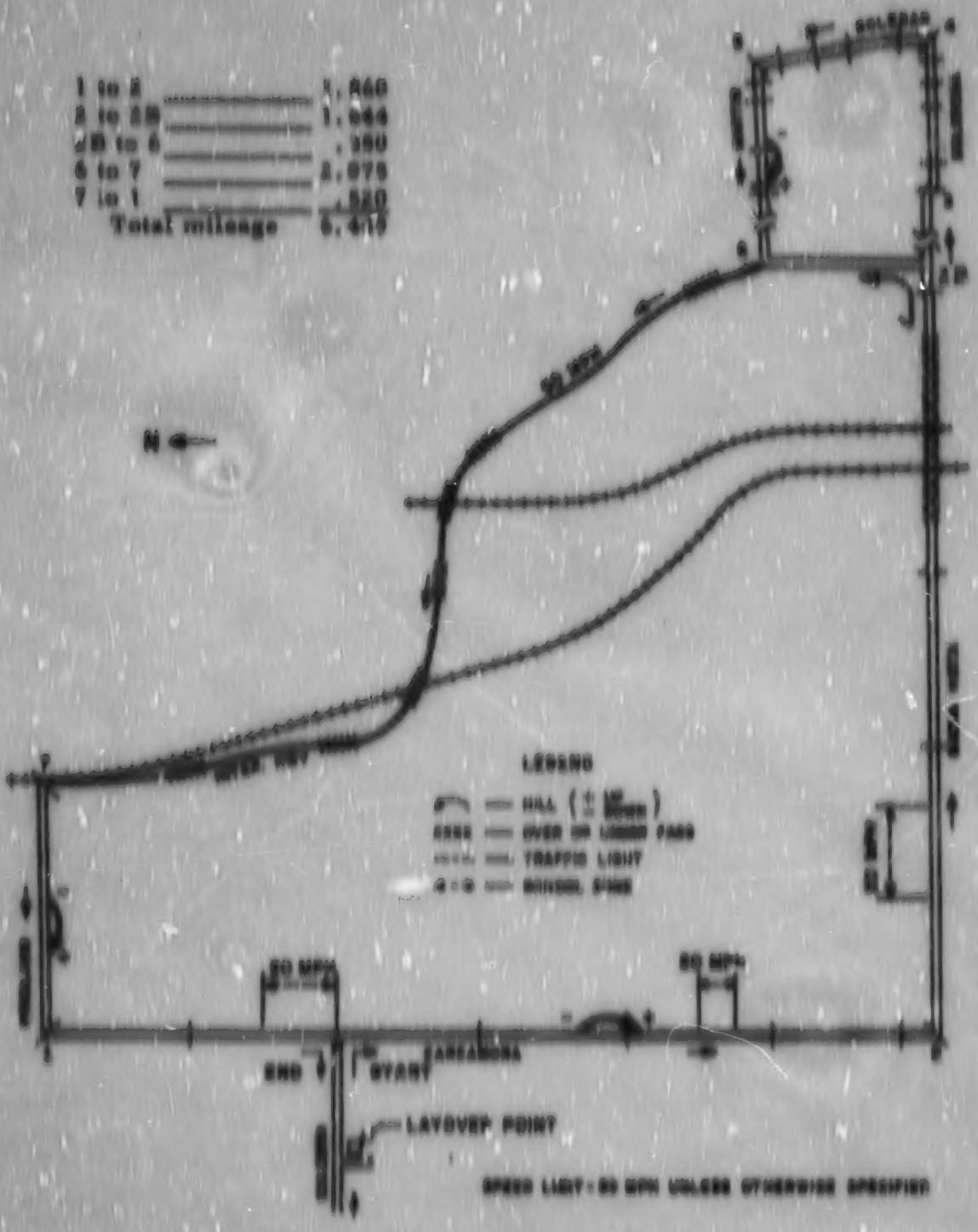

FIGURE 13A. ALTERNATE SAN ANTONIO HEAVY-DUTY GASOLINE TRUCK ROAD ROUTE FOR TRACTOR-TRAILER

FIGURE 14. MANIFOLD VACUUM, VEHICLE AND ENGINE SPEED, AND THROTTLE POSITION INSTRUMENTATION AND RECORDERS

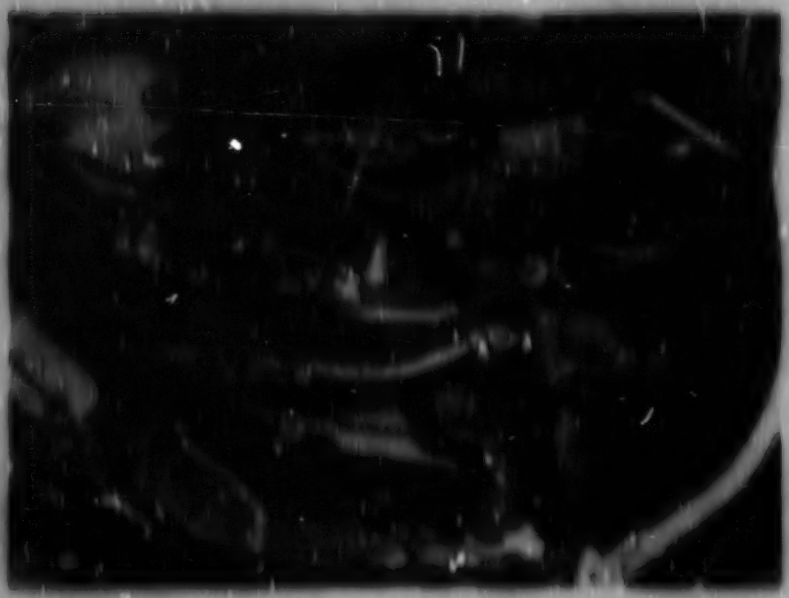

FIGURE 15. ENGINE CARBURETOR THROTTLE POSITION LINEAR TRANSDUCER

(1) $\frac{\text{(observed flywheel horsepower)} \times \text{(time in mode)}}{\text{(total time for one cycle)}} = \frac{\text{bhp-mode}}{\text{one cycle}}$

(2) sum of the $\frac{\text{(bhp-mode)}}{\text{one cycle}}$ for each of the 9-modes = $\frac{\text{(bhp)}}{\text{one cycle}}$

(3) Bhp-hr = $\frac{\text{(bhp)}}{\text{one cycle}}$ × [time (hr) for one complete 9-mode procedure]

For chassis dynamometer tests in which it is impractical to measure flywheel power, engine brake horsepower-hour output was calculated on the basis of fuel consumed by the following equation:

$$\text{Bhp-hr} = \frac{\text{[HHV of fuel]} \times \text{[weight of fuel consumed in pounds]}}{2544.5}$$

HHV (Higher heating value) of Indolene 30 = 20,292 Btu/lb
One bhp-hr = 2544.5 Btu's

The ratio established between flywheel bhp-hr and fuel bhp-hr on six engines was 0.87. This information allows an estimate of bhp-hr, for the 9-mode Federal cycle, to be made for trucks being operated on the chassis dynamometer when the weight of fuel consumed is known.

IV. DESCRIPTION OF CHASSIS DYNAMOMETER, TEST VEHICLES AND PROCEDURES

Since one objective of this study was relate actual road course emissions to chassis dynamometer emissions, a discussion of the chassis dynamometer configuration used and a description of the test vehicles are presented in this section.

A. Chassis Dynamometer Equipment and Operation

The SwRI system used in testing heavy-duty trucks was a Clayton Series C/T-200 single-axle, water brake, chassis dynamometer, shown in Figure 9. Up to 200 hp may be absorbed by the water brake. This dynamometer was coupled to a solid disc flywheel arrangement shown in Figure 16. The flywheels can be coupled in such an arrangement that a minimum of 1500- to 16,000-lb maximum equivalent inertia, with any 250-lb increment in between, can be simulated. This system also incorporates a 50-hp, three-phase AC electric motor that can be used to maintain constant speed operation as either a power absorbing or motoring unit. This motor can be readily disconnected via the motor slider mounts and a large timing belt. The characteristic of the SwRI chassis dyno unit is to follow the "q" load curve; i. e., it closely simulates the operation of a vehicle where load increases exponentially with increasing vehicle speed.

B. Vehicles Tested

Table I lists all the vehicles tested during this project. The top six trucks were used during the road-chassis dynamometer studies. All vehicles were obtained from local rental agencies. The first vehicle tested, the 1966 Chevrolet stake body, was the same vehicle utilized during the previous experimental cycle modifications. The fourth vehicle was a 1969 Ford U-Haul truck which was originally sold in California and was equipped with emission control. The sixth vehicle was a two-axle (single-drive) truck-tractor which was operated on an abbreviated road course with a semi-trailer attached (see Figure 19A). The two trucks subjected to chassis and stationary dynamometer tests are listed at the bottom of Table I. The 54,000-GVW IHC stake with 85,000 miles was the same truck tested in October 1969.

C. Test Procedure

Procedures used during this project will be described in two different categories: (1) road route and chassis dynamometer and (2) chassis and stationary engine dynamometer procedures.

PHOTO BY STAFF PHOTOGRAPHER JOSEPH CAPRIOLO

EL VIETNAMITA DE 21 AÑOS, TOMA EL SOL EN LA PLAYA

CONDENADO EL 1-65

TABLE 1. DESCRIPTION OF TEST VEHICLES

Year	Make	GVW	CID	Cyl.	Body	Date	Mileage	Source
			(Road-Chassis Dynamometer Studies)					
1968	Chev	12,000	250	I-6	Stake	9/1969	16,100	Avis
1966	IHC	24,000	345	V-8	Stake	10/1969	19,800	Hertz
1968	Ford	17,000	330	V-8	Van	9/1969	13,000	U-Haul
1969	Ford	19,000	300	V-8	Van	9/1969	38,000	Ryder
1969	Chev	19,500	350	V-8	Van	11/1969	15,630	Avis
1968	IHC	36,000	450	V-8	Tractor	12/1969	44,765	ABC
			(Chassis-Stationary Dynamometer Studies)					
1966	IHC[a]	24,000	345	V-8	Stake	5/1970	25,000	Hertz
1969	Chev	10,000	250	I-6	Stake	5/1970	16,000	Avis

[a]Same as second listed IHC truck.

1. Road-Chassis Dynamometer Procedure

Each vehicle was tested by the following procedure. First, the truck was given a minor tuneup, including replacement of plugs, points, condenser, air cleaner, and fuel filter. The Sun 1120 electronic engine diagnostic and tune-up unit was used to adjust the engine to factory specifications. In the case of an emission controlled engine, the tuneup and adjustments were in accord with the special recommendations of the manufacturer. Next, the vehicle weight was adjusted so that it was loaded to one-half of its payload. On larger vehicles, drums of water were necessary to achieve this load condition. Then the vehicle was operated on the chassis dynamometer at a wheel speed to result in 2000-rpm engine speed with a maximum variation of ±100-rpm engine speed. Simultaneous continuous NDIR and constant volume bag samples were obtained. The primary test schedule was the 9-mode procedure in the current Federal Register[5] and described in Table 2 (top half). Though the current Federal procedure calls for stationary type engine dynamometer testing, the proposed standards[6] included an alternative chassis dynamometer procedure which, due to the nature of this project, was used exclusively.

TABLE 8. CURRENT FEDERAL AND ORIGINAL CALIFORNIA CONSTANT SPEED PROCEDURE FOR HEAVY-DUTY GASOLINE TRUCKS

FEDERAL CYCLE

Sequence Number	Manifold Vacuum	Time in Mode, sec	Cumulative Time, sec	Weighting Factors
1	Idle	70	70 (1:10)	0.036
2	15 in. Hg	23	93 (1:33)	0.009
3	10 in. Hg	64	157 (2:37)	0.257
4	15 in. Hg	23	180 (3:00)	0.009
5	19 in. Hg	17	197 (3:17)	0.047
6	14 in. Hg	23	220 (3:40)	0.009
7	3 in. Hg	34	254 (4:14)	0.283
8	15 in. Hg	23	277 (4:37)	0.009
9	Closed throttle	43	320 (5:00)	0.021

Engine speed 2000 ± 100 rpm.

An initial 5-min idle, two warmup cycles and two hot cycles constitute a complete dynamometer run.

Note: The California procedure[6] includes a provision for chassis dynamometer vehicle speed 35 ± 2 to 40 ± 2 to give engine speed close to 2000 rpm.

ORIGINAL CALIFORNIA CYCLE*

Sequence Number	Manifold Vacuum	Time in Mode, sec	Cumulative Time, sec	Weighting Factors
1	3 in. Hg	15	15 (0:15)	0.060
2	Closed throttle	10	25 (0:25)	0.005
3	3 in. Hg	20	45 (0:45)	0.200
4	Closed throttle	50	95 (1:35)	0.045
5	10 in. Hg	20	115 (1:55)	0.210
6	Closed throttle	10	125 (2:05)	0.005
7	10 in. Hg	65	190 (3:10)	0.310
8	Closed throttle	10	200 (3:20)	0.005
9	15 in. Hg	40	240 (4:00)	0.160

*Emission data are integrated over the closed throttle modes and read for the last 3 seconds of the steady state modes.

As requested in the letter of May 20, 1969[7], hydrocarbon (HC) and carbon monoxide (CO) emissions were also obtained under the original California 9-mode procedure listed on the bottom half of Table 2. The major difference in the two procedures is (1) the original California method included a closed throttle decel between each mode and (2) the length of cycle was 30 min for the Federal and 16 min for the original California. An alternative exists in the current Federal procedure which permits an idle at the beginning and at the end of the four modes, reducing the overall time, if desired, by 140 sec. The procedure for operation and data reduction was in accord with References 8 and 9.

Next, the vehicle was further instrumented and operated on the road route and operating parameters and bag emissions data via the constant volume sampler obtained during replicate runs. Then the vehicle was operated on the chassis dynamometer at 3000 rpm and steady-state HC, CO, CO_2, and NO concentrations recorded throughout the manifold vacuum (power) range of the engine. These data were then plotted to provide insight in modifying the current Federal procedure to imitate the road results. This entire procedure required on the order of three weeks per truck to conduct.

2. Chassis-Stationary Dynamometer Procedures

Two vehicles were used during the second phase of testing. Because five of the six vehicles tested during Phase I were no longer in the San Antonio area, only one vehicle, the 1966 IHC 345 CID truck, was retested. Each vehicle was prepared for test as described for the road studies. After a tuneup, each vehicle completed a minimum of two 9-mode Federal cycles on the chassis dynamometer. During all of the tests, simultaneous continuous NDIR and constant volume bag samples were obtained. After completing the Federal 9-mode cycles on the chassis dynamometer, the engine was removed from the truck for stationary engine dynamometer evaluation. The engine was then installed on the stationary engine dynamometer, and the timing, dwell, and idle RPM were checked to insure that the basic conditions were the same as they were during the chassis evaluation. Using two sampling systems, CVS and Continuous, a minimum of two 9-mode Federal cycles were conducted.

At the request of the Project Officer, additional studies were undertaken to determine the emissions under a variety of loads at a single engine operating speed.

One of the apparent deficiencies of the current Federal test method is the minimal (three) number of power modes at the 3000-rpm engine speed. It was felt that these modes may not adequately reflect an engine's emissions behavior and a more complete map warranted some study. The procedure included operating the engine between 0 and 100 percent full load in 10 percent increments at peak torque engine speed. Bag samples of exhaust from individually operated modes and a composite bag were analyzed. Also of importance was a low idle and closed throttle motoring (deceleration) condition.

The procedure which was used is shown on Table 5. Peak torque engine speed was selected on the basis of earlier obtained road route data and was agreed to by the Project Officer.

TABLE 5. TEST PROCEDURE USED TO MAP EMISSIONS AT PEAK TORQUE ENGINE RPM

Conditions	Load	Sample Time (each mode)
1	100% → 20% at 10% intervals	2 min
2	20% → 100% at 10% intervals	2 min
3	Close throttle (motoring)	2 min
4	Idle - Zero load	2 min
5	100% → 20% at 10% intervals	2 min
6	20% → 100% at 10% intervals	2 min

Note: During conditions 1 and 2, individual bag samples were collected and measured for each load interval. Conditions 5 and 6 were a single composite bag sample consisting of all the power conditions.

The peak torque engine rpm was obtained from the advertised manufacturer's specifications. For warm-up, the engine was operated at 50-percent load and peak torque rpm for 5 min. After the warm-up procedure, the load was increased to 100 percent (WOT) at peak torque speed. After stabilizing in this condition for 30 sec, both of the sampling systems obtained exhaust gas samples. During power conditions below 50 percent, the engine was allowed to stabilized for 1 min before samples were obtained. The reason that the engine was only allowed 30 sec to stabilize at the 50-percent power level and above was the tremendous heat input to the CVS sampler. When operating above the 50-percent load level during conditions 1, 2, 5, and 6 in Table 5, it was necessary to cool the inlet temperatures to the positive displacement blower to 110°F before starting the next power conditions. This cooling period was necessary to prevent possible ignition of the activated charcoal filter shown in Figure 2.

Fuel consumption and airflow for each engine were obtained separately from the emissions test. The fuel consumption was obtained over a 2-min time interval a minimum of two times. Airflow measurements were obtained using a Merriam 300-cfm laminar flow element. This information completed the stationary engine dynamometer work. The engine was removed and installed in the truck for one more group of Federal 9-mode cycles before returning the vehicle.

V. RESULTS

The discussion of the results is in six parts. The first four parts are concerned with comparisons of Federal to original California, road to chassis, road to engine, and engine to chassis data in which the current Federal 9-mode constant speed cycle is the basis for comparison. The last two parts cover the results of limited exploratory studies of two vehicles using power modes at peak torque speed and a relationship between brake specific and concentration emissions.

A. Comparison of Current Federal and Original California 9-Mode Constant Speed Procedures

As requested in the letter of May 20, 1969, HC and CO emissions were obtained by the current 1970 Federal constant engine speed (2000 rpm) procedure for emissions from heavy-duty gasoline trucks and by the original California procedure. Both schedules are listed in Table 3.

A comparison of the results of the Federal and original California procedures, in summary form, is listed in Table 4. In each case, the HC emissions were substantially less by the original California procedure than by the current Federal procedure as noted by the comparison ratios of 0.22 to 0.91. CO, however, was greater by the Federal cycle for five of the six trucks as indicated by comparison ratios greater than 1 (1.143 to 2.000). The last truck, a 1968 IHC tractor, produced an opposite trend in CO relative to the other five trucks with a ratio of 0.347 (Federal/California).

These differences, especially the gross difference in HC emissions, are attributed to the significant differences in the operating schedules. The following lists the cumulative time at various throttle settings and points up the major differences in mode times.

Throttle Setting	Time, sec	
	California	Federal
Idle	0	70
Closed Throttle	80	41
1-in. Hg Manifold Vacuum	35	34
10-in. Hg Manifold Vacuum	25	44
15-in. Hg Manifold Vacuum	40	92
19-in. Hg Manifold Vacuum	0	17
	240 sec/cycle	300 sec/cycle

TABLE 4. COMPARISON OF EMISSIONS FOR FEDERAL AND ORIGINAL CALIFORNIA TEST PROCEDURES

Vehicle Description					NDIR HC, ppm hex.*			CO, %*		
Year	Make	CID	GVW	Body	Federal	Calif.	Ratio†	Federal	Calif.	Ratio†
1968	Chev	250	10,000	Stake	276	901	0.306	2.47	2.11	1.170
1966	IHC	345	24,000	Stake	277	1153	0.240	2.7	2.2	1.227
1968	Ford	330	17,000	Van	342	1270	0.269	2.3	1.8	1.277
1969	Ford	300	15,950	Van	274	1235	0.221	0.84	0.42	2.000
1969	Chev	250	19,500	Van	178	443	0.401	3.58	3.13	1.143
1968	IHC	450	26,000	Tractor	172	340	0.505	1.60	4.61	0.347

*Based on Dilution Ratio $\frac{14.5}{CO_2 + 0.5\,CO + 10.8\,HC}$

†Comparison Ratio, Federal/California.

The large number of closed throttle decelerations of the original California cycle and their weight in the computation, according to Table 3, are the major contributors to the HC difference. For complete emissions results for all runs summarized in Table 4, please refer to Table B-1.

B. Comparison of Road and Dynamometer Results Using the Constant Volume Sampler

Emissions of hydrocarbons (HC) by flame ionization analysis and carbon monoxide (CO) and nitric oxide (NO) on a grams per pound of fuel consumed are graphed in Figures 17 through 22. The first bar is the average road course emissions; the other bars represent emissions with the Federal and Alternate Federal procedures (2 idles for 17 min, 40 sec, instead of 4 idles for 20 min), original California procedures, and a number of modifications to the Federal schedule. The bar charts summarize the average of the complete run data listed in Tables B-2 through B-7. Comparing the road and the Federal results, it is apparent that, overall, the HC emissions were not greatly different except for the 1958 Ford, 330 CID, 17,000-lb GVW truck, and the 1968 IHC, 450 CID, 26,000-lb GVW tractor (Figures 19 and 22). CO emissions relative to the road were less for the Federal runs, except for two trucks, the 1968 Ford, 300 CID, 15,000-lb GVW and the 1968 IHC tractor, 450 CID, 26,000-lb GVW (Figures 20 and 22). NO emissions generally were greater by the Federal procedure than by the road course though in two instances they were about the same. Considering the total cumulative height of the bars, which represent all three contaminants on an approximately equal basis, the Federal and the road emissions generally are not the same. However, the magnitude of the disagreement is not nearly as great for the six vehicles studied as was indicated during the limited comparisons made during the previous study using the experimental nonsteady speed driving schedules. [2]

The current Federal procedure permits an alternative of running two idles instead of four, with one at the beginning and one at the end of the four cycles. Two vehicles, the 1968 Ford (Figure 19) and 1969 Ford (Figure 20) were operated on the alternate procedure. Although the continuous NDIR sampler HC and CO results were identical, the HC (FIA), CO, and NO by the constant volume sampler showed some variation (Figures 19 and 20). Overall, the constant volume data seemed to indicate emissions more nearly like the road for the 1968 330 CID Ford but less like the road in terms of CO for the 1969, 300 CID Ford.

Modifications of the current 20-min Federal procedure were investigated in an attempt to improve on its level of agreement with the road course. Three modifications were tried with the first vehicle, the 1968 Chevrolet 10,000-lb GVW stake. Figure 17 shows that Modification No. 1 resulted in essentially the same emissions as those obtained during the road tests.

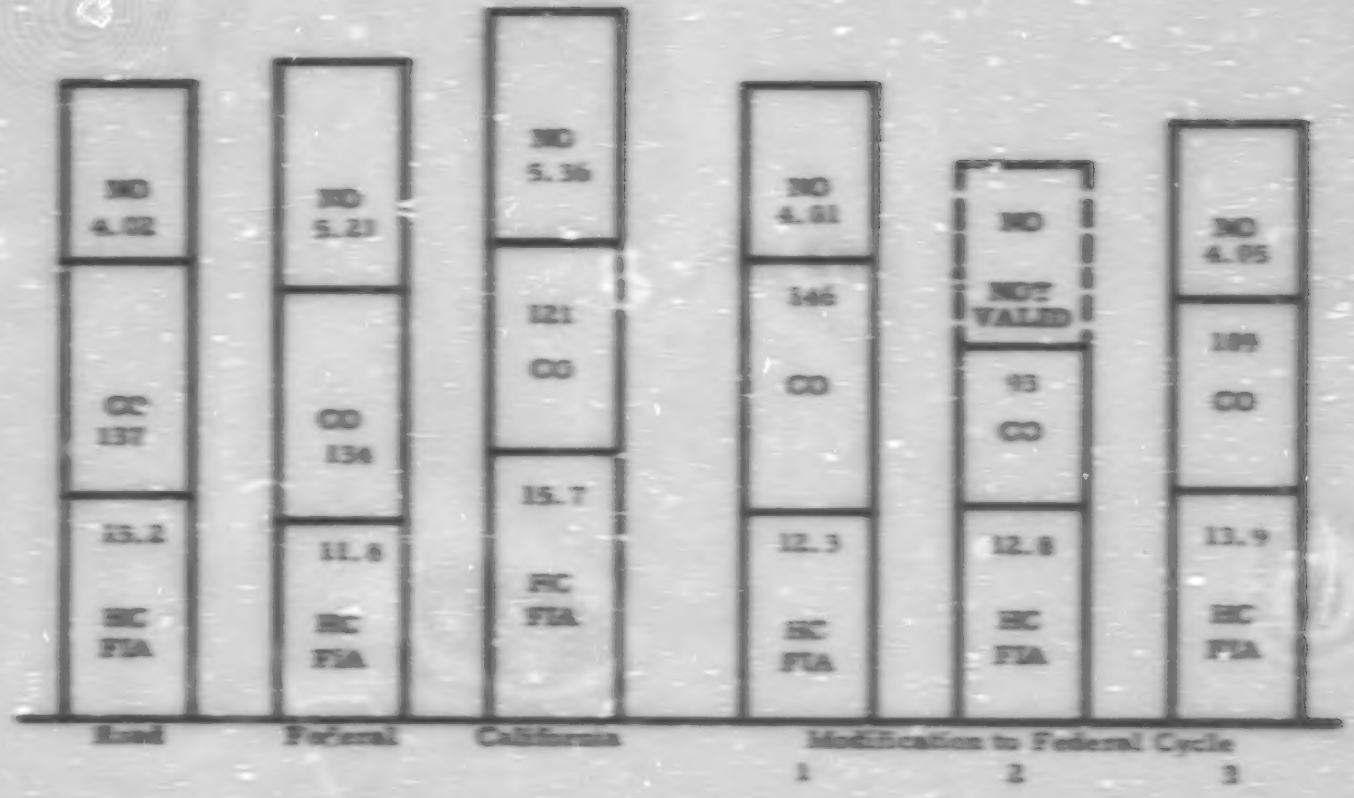

FIGURE 17. ROAD AND DYNAMOMETER RESULTS, 1966 CHEVROLET
250 CID, 10,000-LB GVW STAKE
Constant Volume Sampler, Grams Per Lb of Fuel

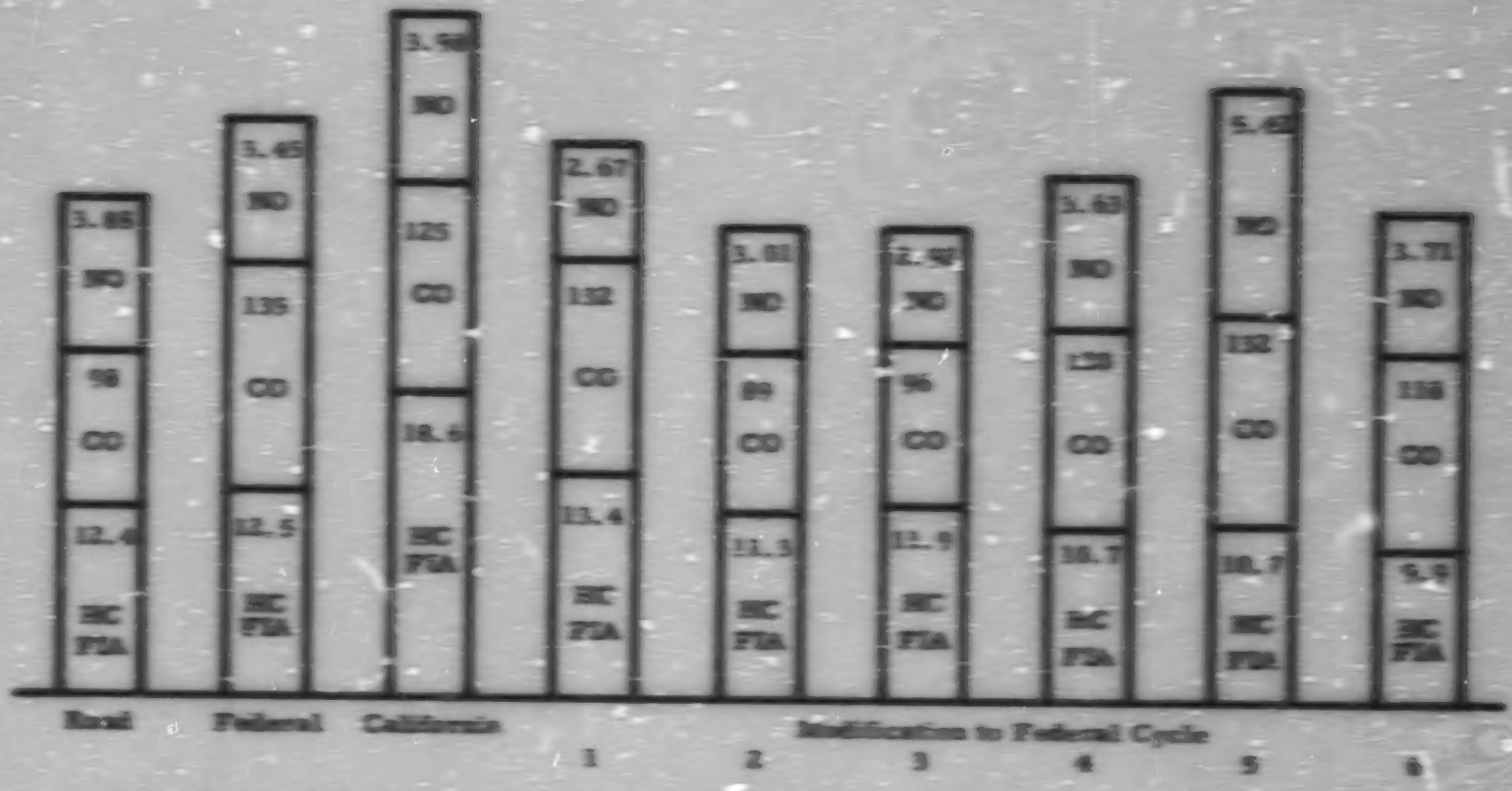

FIGURE 18. ROAD ACID DYNAMOMETER SERIES-25, 1966 SIC, 345 CID, 24,000-LB GVW TRUCK
Constant Volume Sampler, Grams Per Lb of Fuel

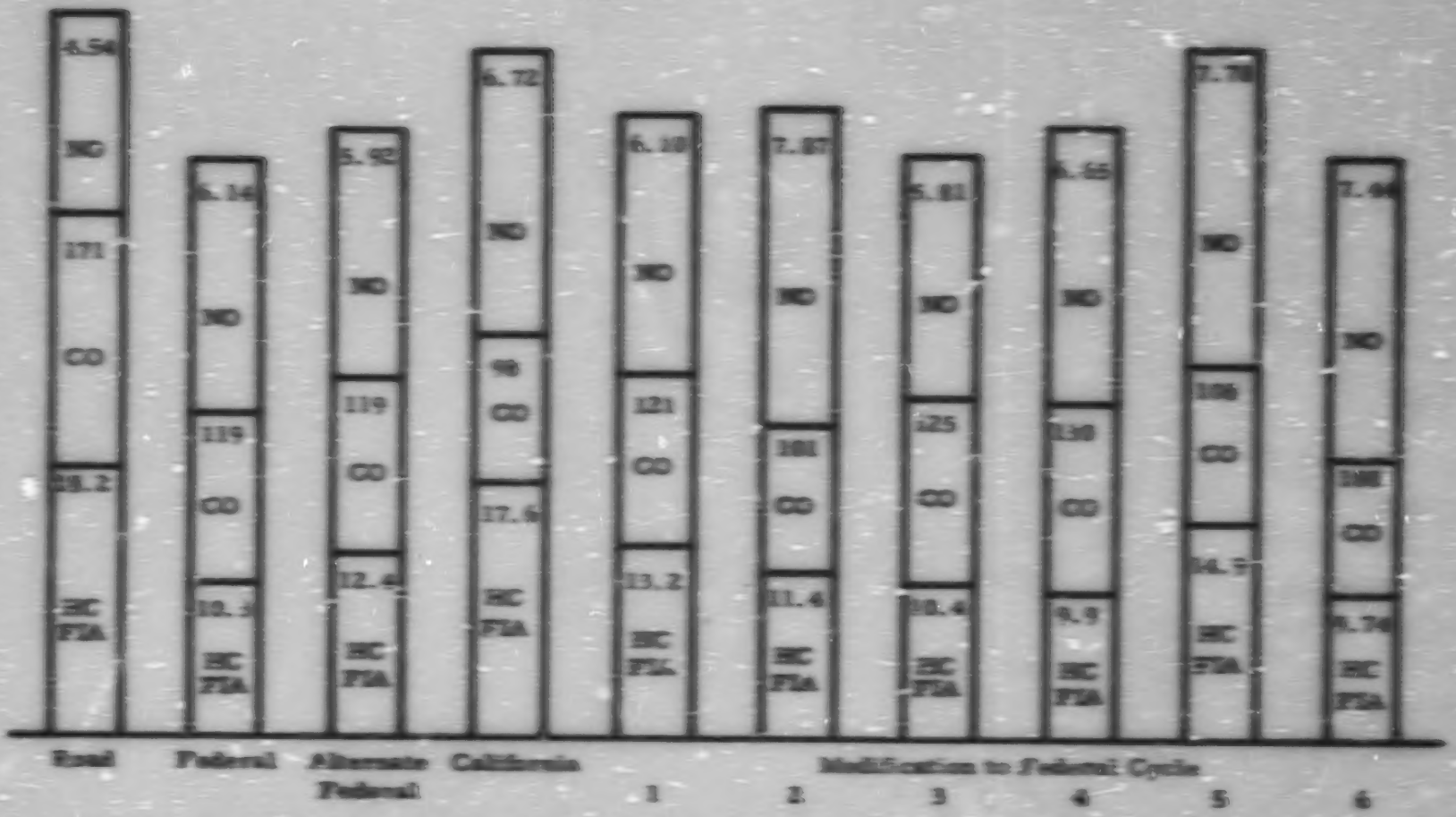

FIGURE 19. ROAD AND DYNAMOMETER RESULTS, 1968 FORD, 330 CID, 17,000-LB GVW TRUCK
Constant Volume Samples, Grams Per Lb of Fuel

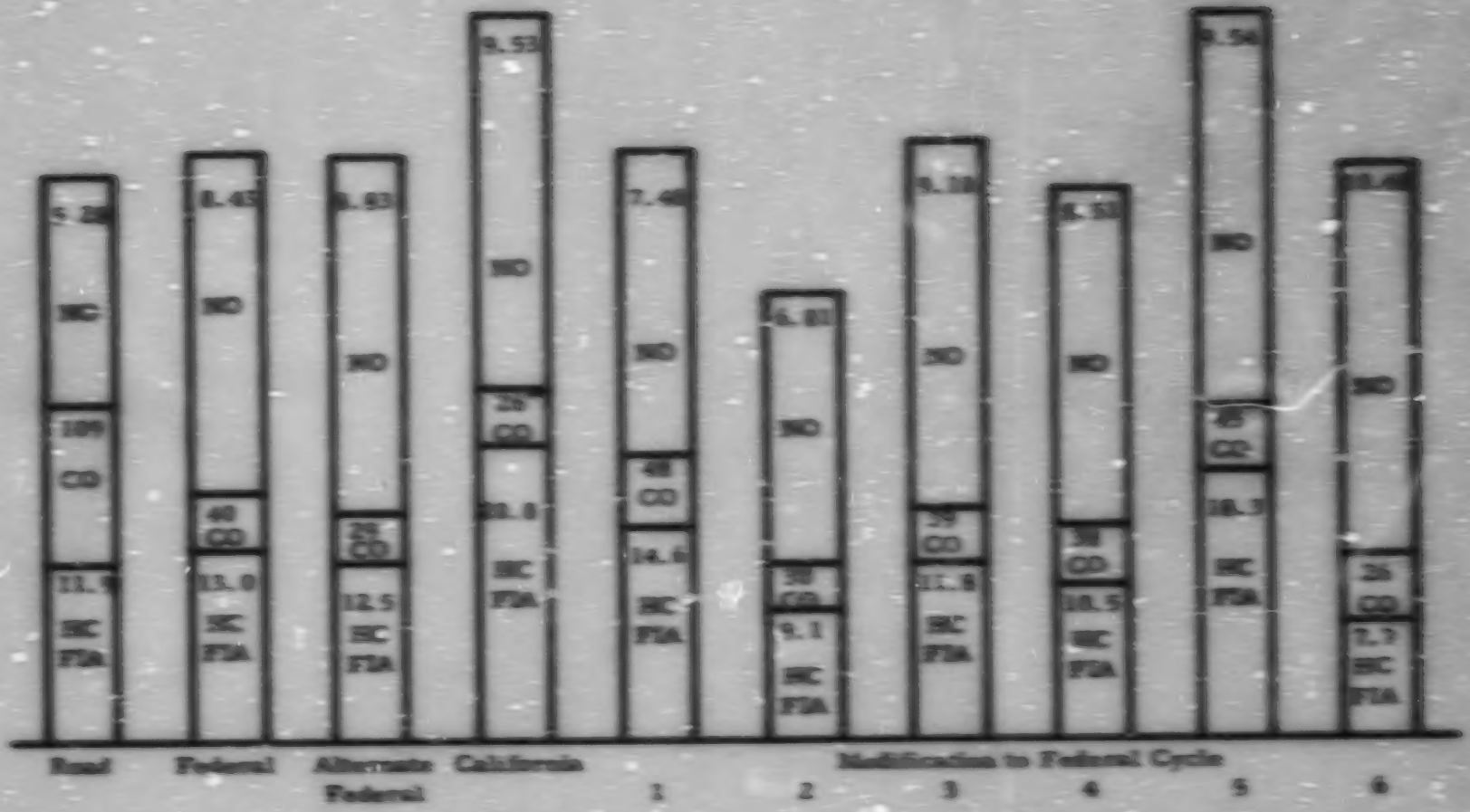

FIGURE 23. ROAD AND DYNAMOMETER RESULTS, 1969 FORD, 302 CID, 15,000-LB GVW VAN
Constant Volume Samples, Grams Per Lb Fuel

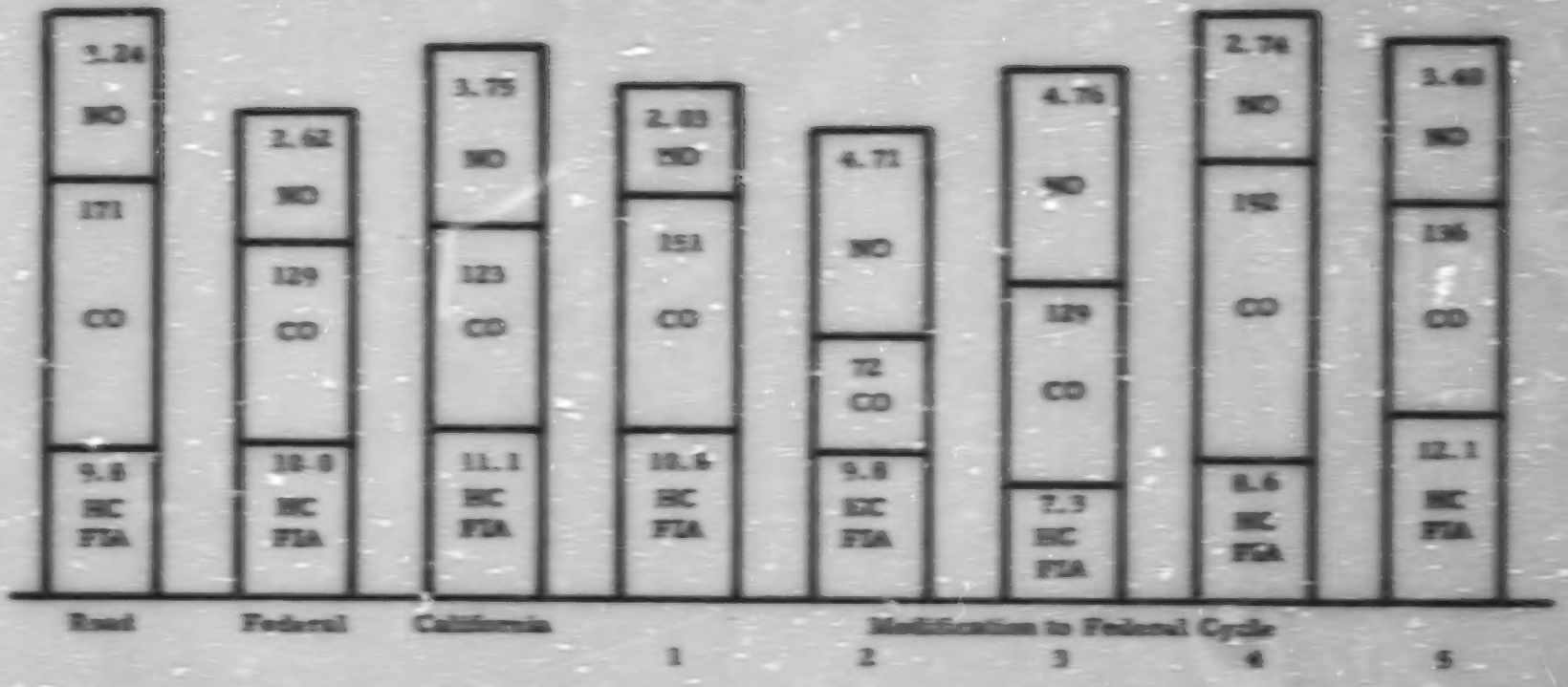

FIGURE 21. ROAD AND DYNAMOMETER RESULTS, 1969 CHEVROLET, 350 CID, 14,500-LB GVW VAN TRUCK
Constant Volume Sampler, Grams Per Lb of Fuel

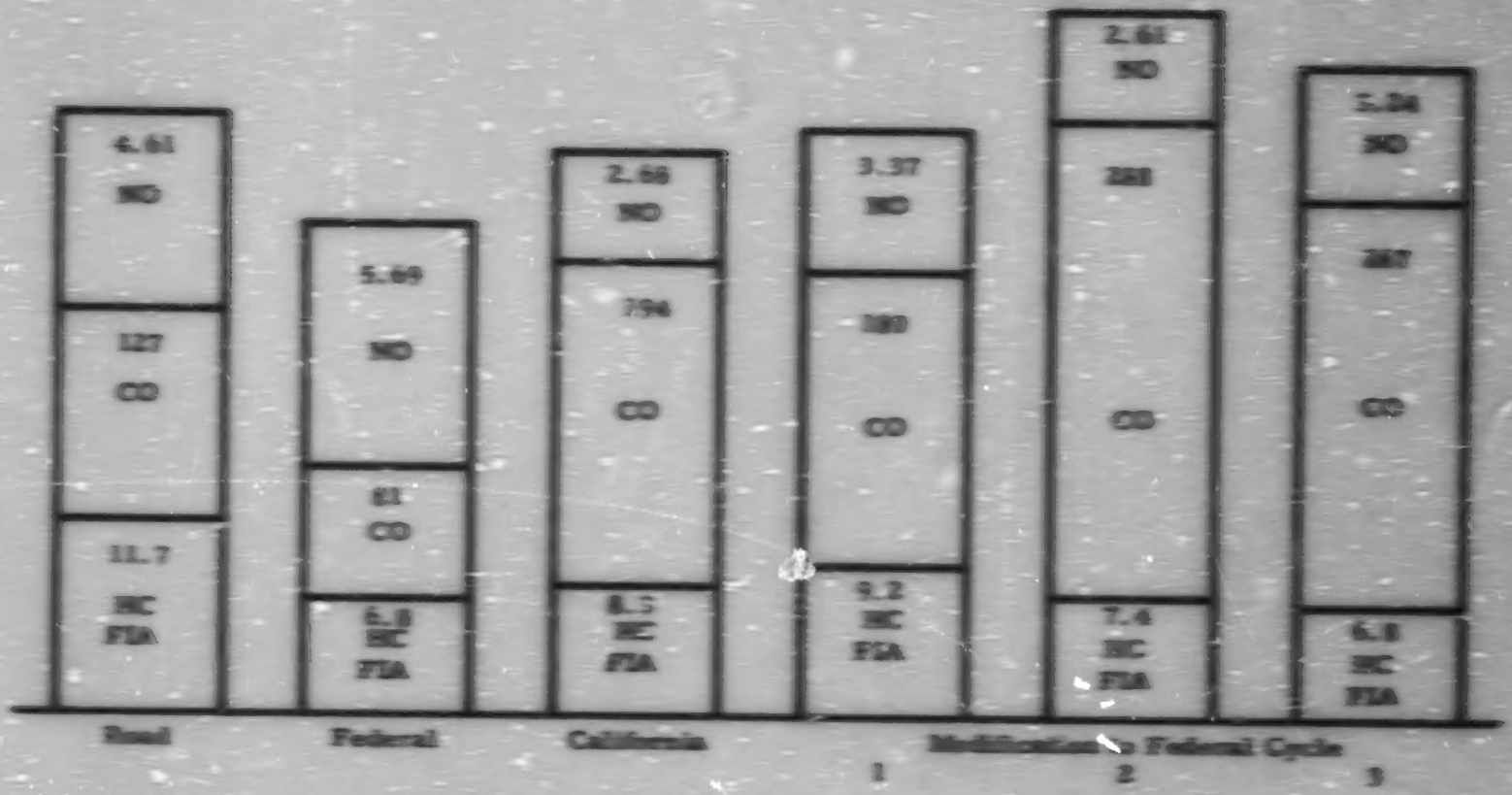

FIGURE 22. ROAD AND DYNAMOMETER RESULTS, 1968 HC, 450 CO, 26,000-LB GVW TRACTOR
Constant Volume Samples, Grams Per Lb of Fuel

Modification No. 1 involved changing the mode 3 intake vacuum from 10 to 19 in. of Hg (see Table 3). Modification No. 2 changed the mode 7 vacuum from 3 to 5 in., while Modification No. 3 was a combination of modes 1 and 2.

Initial experiments with the next vehicle, the 1966 IHC, 349 CID, 24,000-lb GVW truck illustrated the need for insight on the effect of manifold vacuum changes on emissions. Since the constant volume sampler results were not grossly different between the road and Federal procedures, it was felt that only minor modifications to the cycle such as manifold vacuums and mode durations should be attempted. Variations in engine speed, overall cycle length, or number of modes were not included as variables.

Similar to the technique reported in Reference 10, a curve of CO, HC, and NO versus engine vacuum at a constant 2000-rpm engine speed was found helpful. The relationship of these exhaust parameters with power output (VAC) is plotted in Figures B-1 through B-3. As an example of how Figure B-1 can be of help, if the 10-in. vacuum in mode 3 was changed to a 19-in. vacuum, the HC would increase and the CO and NO decrease. If we were looking for an increase in CO and HC with a slight change in NO, changing mode 3 to 15 or 16 in. would give this type of a change. The magnitude of change, however, as reflected by the constant volume sampler, can only be estimated from these curves. Neither Modification 1 or 2, which improved the agreement between road and Federal results for the 1966 Chevrolet, were as helpful in improving the correlation, though overall they were better than the unmodified Federal cycle. These results and those for another five modifications (listed in Table B-3 and summarized on Figure 18) followed the trend indicated by the exhaust emission curves, Figure B-1, for each change of vacuum level. The amount of change depended on the length of time that the mode which was modified had relative to the length of cycle.

There was no single modification that brought the Federal cycle emissions for all three compounds (HC, CO, and NO) to the same level as the road route. The Federal cycle without any modification produced about the same HC emission as the road route. However, the CO was too high and the NO a little low. Changing the 3-in. vacuum in mode 7 to a 9-in. vacuum gave the best results for the CO and HC emissions. However, the NO emissions were below the road route. The California cycle had close agreement of NO but was much too high with HC and CO. The best NO agreement came by changing the 16-in. vacuum in modes 4 and 8 to a 9-in. vacuum. This change resulted in the HC being too low and the CO close, but still too high.

In a similar manner, the other four trucks were operated on modified cycles with the detailed results listed in Table B-4 through B-7 and summarized on Figures 19 through 22. To assist in determining which modifications would be of help, manifold vacuum curves (Figures B-4 through B-8) were employed. In all cases, the first two modifications were the

10- to 19-in. (mode 3) and 3- to 5-in. (mode 7) as these seemed helpful for the first two vehicles studied.

To summarize the success of the modifications in bringing the Federal cycle emissions more in line with the road route, Figure 13 shows the road route and single best modification. The method used to determine the best modification was to assume equal importance to each emission and rank order the comparison ratios of the modified cycle results relative to the road course. Then the total ranking was determined by adding the individual emission ranking. The lowest total indicated the best modification. It may be noted that no one modification was found to be universally best for the six trucks studied, and that the degree of improvement in some cases fell somewhat short of the road emissions. For four of the six vehicles, changing mode 3 from 10- to 19-in. intake manifold vacuum was identified as the best modification. When good agreement was found, it was inherent and not necessarily due to the modification. One of the most perplexing problems was the repeated difficulty of making changes that improved agreement of one emission at the expense of decreasing the agreement of one or both of the other emissions. However, strict reflection of road emissions is not necessarily the goal of this work because of the general arbitrary nature of the road course in its layout and traffic conditions.

C. Comparison of Emissions Obtained from Stationary and Chassis Operated Engines

Although the California 9-mode procedure lists a stationary engine dynamometer procedure as an alternative to the chassis method, the final Federal procedure eliminated the chassis method in deference to a stationary operated engine test. This results in a difficulty in conducting surveillance type or confirmatory type tests in vehicles unless the engine is removed and adapted for test bed operation. To study in a limited way, the potential equivalency of the two test methods, a series of chassis tests were run on two vehicles, a 44,000-GVW IHC stake with V-8, 345 CID engine and an I-6 Chevrolet 250 CID stake. The IHC was the same as that earlier tested while the Chevrolet was as similar to the previously tested vehicle as possible. Both vehicles were described in Table 5. Once the chassis tests were conducted, the engines were removed and Federal 9-mode cycles run on the engine test bed.

Figure 14 is a bar chart comparing HC, NO, and CO emissions on a concentration basis (by continuous NDIR; the Federal method) for the two trucks. The comparison shows one engine produced slightly more exhaust emissions on the chassis while the other truck produced slightly less emissions relative to the engine procedure. The values shown are averages of several repetitive runs.

FIGURE 23. EMISSIONS FROM ROAD, FEDERAL AND SPECIAL TEST MODES CATEGORIES
Concrete Volume Sampler, Cases For 1/2 of Pad

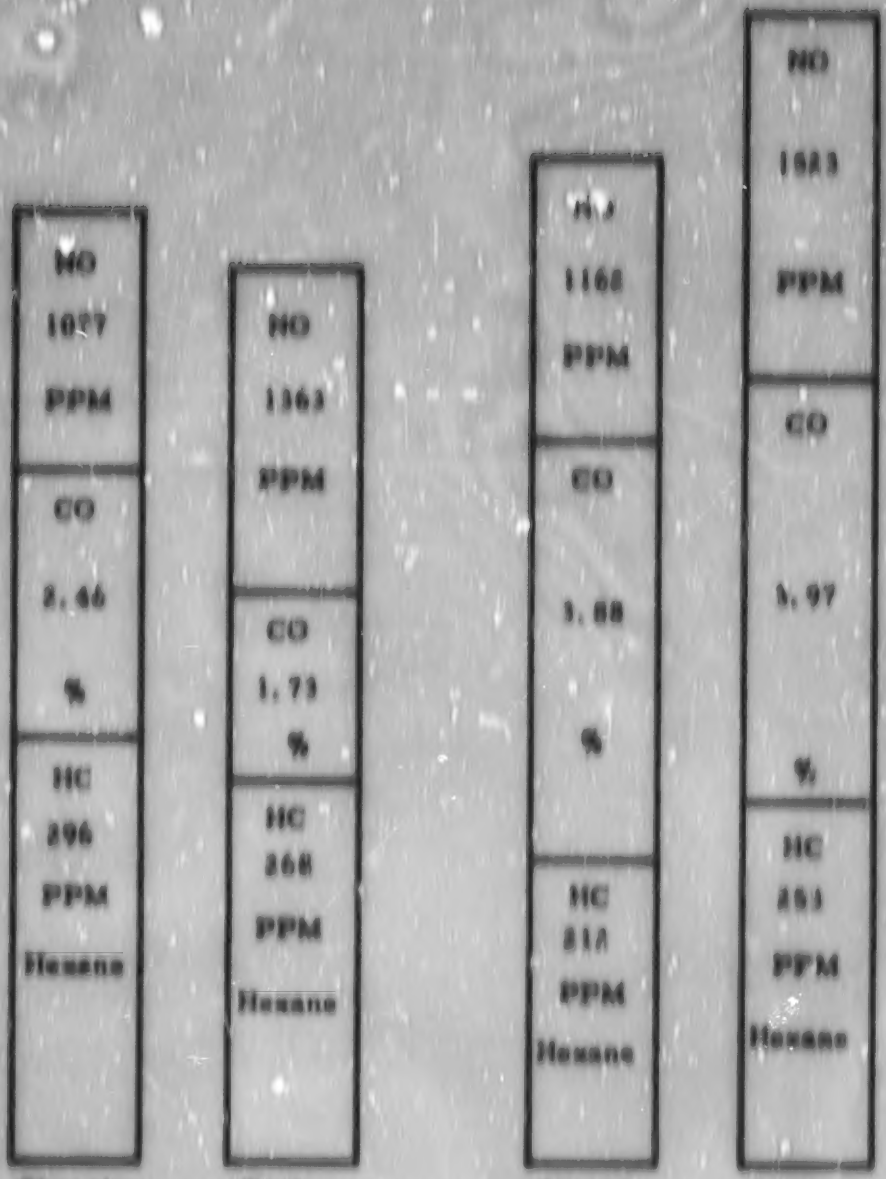

FIGURE 16. COMPARISON OF FEDERAL 9-MODE CONTINUOUS NDIR EMISSIONS USING CHASSIS AND STATIONARY DYNAMOMETER PROCEDURES

Figure 35 is a similar bar chart comparison in terms of grams per pound of fuel consumed using dilute bag samples of the full 20-min run via the constant volume sampler. By this method, the chassis results were generally lower overall than the engine, but not particularly lower in the case of the IHC. These comparisons are based on repetitive run data contained in Appendix C of this report. Though the results of these two vehicles are encouraging, a larger number and variety of vehicles should be studied before equivalency can be demonstrated.

D. Comparison of Earlier Obtained Road Emissions to Chassis and Engine Results

Discussed in Section B was the comparison of road and chassis constant volume sampler results on a gram per pound of fuel burned basis. The engine-chassis data presented in Section C can be compared to the previously obtained road route to illustrate the relationship between road and test bed emissions. This is done in Figure 36 for the IHC truck and in Figure 37 for the Chevy. Though the IHC vehicle was the same unit tested in September 1969, almost 3000 miles were accumulated in the 6 months between tests. Since there was good agreement between road and chassis in September 1969 and good agreement adjudged between chassis and engine in April 1970, it may be concluded that good agreement between road and engine dynamometer results was demonstrated.

Using this same line of reasoning, the Chevy engine (test bed) to road results seem reasonably good though not as close overall as the IHC. It must be noted that the Chevy truck and engine tested in April 1970 was not the same truck evaluated in August 1969 though it was as similar as possible. During the time delay, a change in ownership and location of the original vehicle prevented our retesting the Chevrolet. As in the case of the engine-chassis dynamometer procedure relationship, this limited number of tests should not be considered conclusive. Though more vehicles should be similarly studied, the two truck results seem to indicate that the engine-road results will be comparable if the road and engine data remain comparable to the chassis procedure.

E. Exploratory Studies of Engine-Vehicle Mode Emissions CVS and Continuous NDIR Analysis

At the request of the Project Officer, limited study and experimentation were initiated to explore the potentialities of an abbreviated engine exhaust emissions map. Such a procedure involves operating the engine at various speeds and loads that fairly well define or include operating points normally encountered by the engine-vehicle. For example, such an approach was independently taken by SwRI and the Engine Manufacturers Association in their respective studies of diesel emissions procedures.

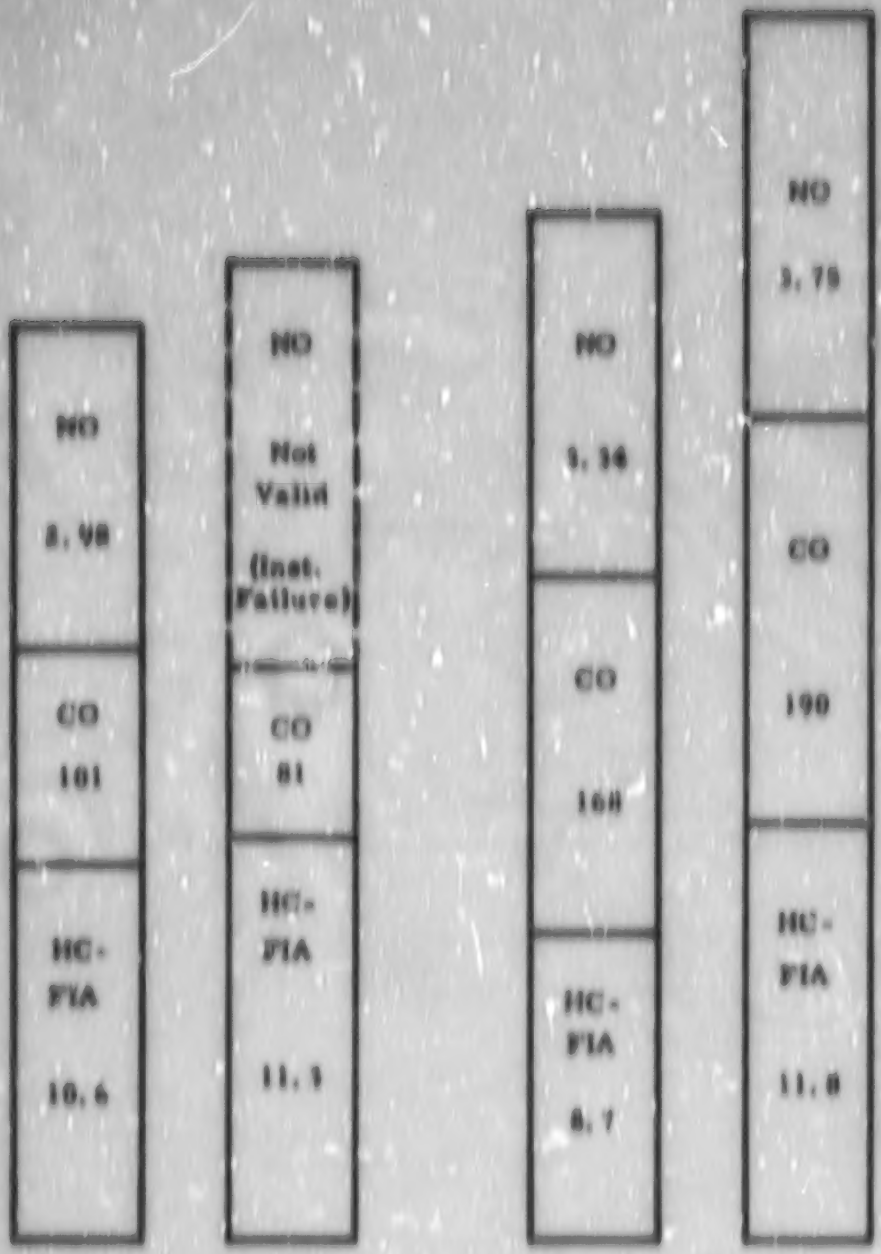

FIGURE 15. COMPARISON OF FEDERAL 9-MODE CONSTANT VOLUME EMISSIONS USING CHASSIS AND STATIONARY DYNAMOMETER PROCEDURES

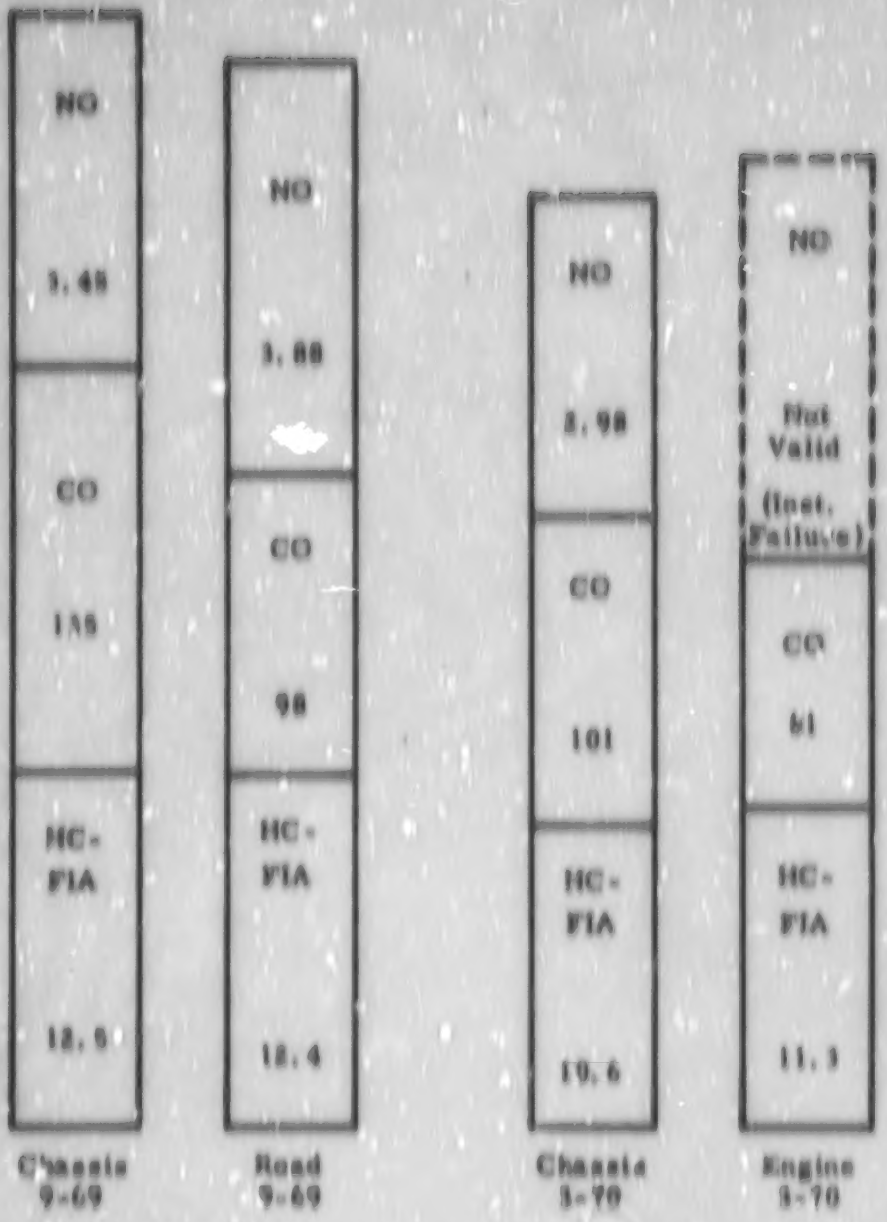

FIGURE 26. COMPARISON OF CONSTANT VOLUME SAMPLER RESULTS FOR 1966 IHC, 345 CID FROM CHASSIS-ENGINE DYNAMOMETER TO EARLIER ROAD ROUTE-CHASSIS DYNAMOMETER DATA - GRAMS OF CONTAMINATE PER POUND OF FUEL

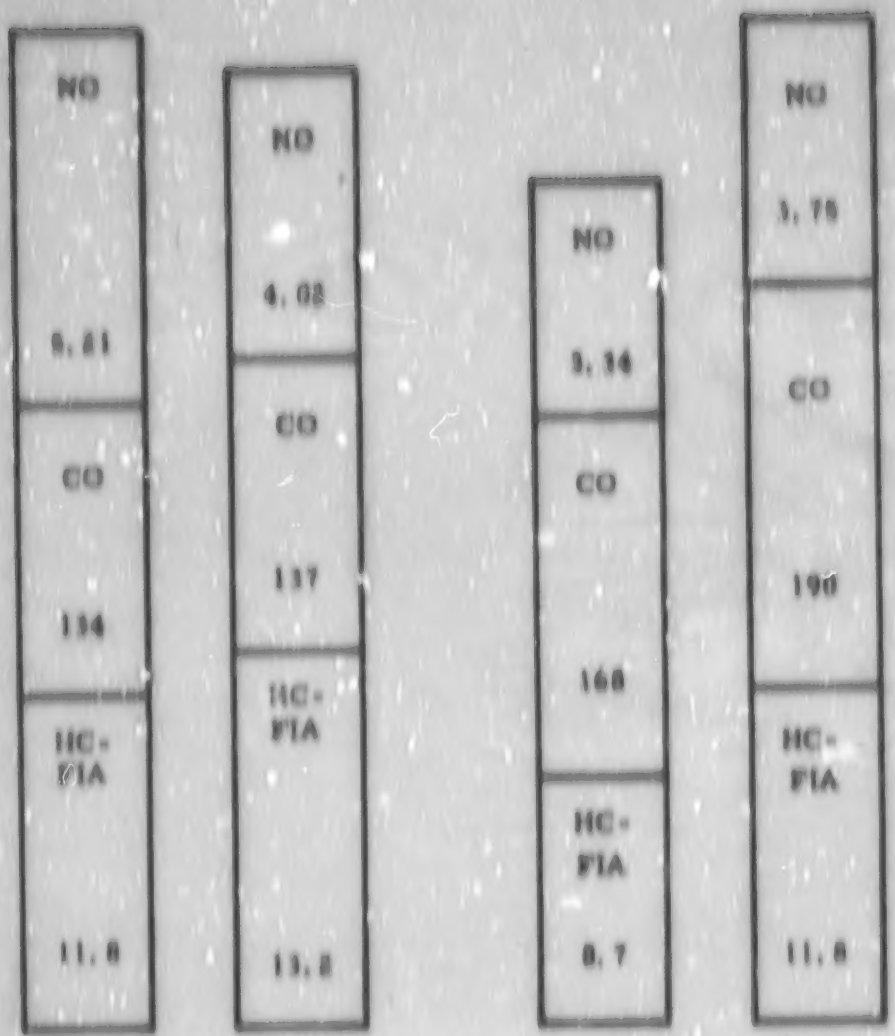

FIGURE 17. COMPARISON OF CONSTANT VOLUME SAMPLER RESULTS FOR A 1968 AND A 1969 CHEVY, 350 CID FROM CHASSIS-ENGINE DYNAMOMETER TO EARLIER ROAD ROUTE-CHASSIS DYNAMOMETER DATA - GRAMS OF CONTAMINATE PER POUND OF FUEL

There evolved a procedure whereby the engine dynamometer or chassis-engine dynamometer system is subjected to a 13-mode procedure for CO, HC, and NO consisting of 0-, 25-, 50-, 75-, and 100-percent full power at both max rated and peak torque (or 60 percent of rated, whichever is higher) speeds plus a low idle. Though this procedure per se is not useable and inappropriate for gasoline-powered trucks, a procedure of this type, applicable to gasoline engines and engined vehicles, was felt worthy of some study. It could remedy some obvious shortcomings of the Federal procedure by including more power levels at closer spaced intervals.

To this general end, a series of experiments was conducted with both the IHC and Chevy vehicles, both chassis and stationary operated. Two engine speeds, peak torque and rated or governed rpm, were initially of interest. From an analysis of engine rpm traces of the six trucks driven on the San Antonio road route, it was evident that engine speed was seldom in the range of rated speed or even governed speed. Peak torque speed seemed to be a more appropriate operating point and is, of course, uniquely defined for each engine. Using 10 percent power increments, the engine was mapped simultaneously with the constant volume and continuous samplers.

Tables 5 and 6 list pertinent engine operating values such as bhp, intake vacuum, airflow, fuel flow, etc., for the IHC and Chevy trucks, respectively. Presented data describe each operating point and were used in expressing the emissions measurements on a brake specific or fuel consumed basis. The particular dynamometer employed did not allow operation at 10- and 0-percent load without partial motoring which was not done. Running light loads, at least the 10-percent indicated power point, should not be difficult on most stationary machines but zero indicated power will be very difficult, without motoring, unless the engine is uncoupled from the dynamometer. In vehicle tests, this can be done by declutching the transmission. Operation at this "high-idle" condition however will not be as stable as under loaded conditions.

Tables 7 and 8 list the CVS, HC-FIA, CO, and NO emission results for the IHC and Chevy trucks on the basis of grams per 3-min test, grams per flywheel brake horsepower-hour, and grams per pound of fuel consumed. The data are tabulated on a decreasing and increasing power mode basis (individual CVS bags), then for a composite of the peak torque power modes (composite bag). Also listed are the low idle and the closed throttle deceleration at peak torque rpm bag results.

A rough comparison of the Table 7 results indicates some discrepancies in that the measurements do not in all cases replicate one another. It is uncertain whether the lack of agreement in flame hydrocarbons, CO, and NO at 60, 70, and 80 percent of maximum power can be attributed to errors in sampling and analysis or to engine mode sequence and history.

TABLE 5. [illegible] FOR 1994, 350 CID,
CHEVROLET-STATIONARY DYNAMOMETER
(2400 rpm - Peak Torque Speed)

Load	Flywheel Hp, obs	Work, hp-hr	Torque, ft-lb	Airflow lbm/min	Fuel Flow lbm/hr	Manifold Vacuum, in. Hg
20	10.85	0.34	33.0	29.28	0.[illegible]55	18.1
30	15.98	0.50	49.5	33.45	0.[illegible]30	16.3
40	20.11	0.57	66.0	41.48	0.[illegible]95	14.4
50	25.13	0.86	82.5	47.92	0.[illegible]50	12.5
60	30.16	1.00	99.0	61.74	0.[illegible]70	9.2
70	35.18	1.17	115.5	69.86	0.[illegible]25	6.8
80	40.21	1.34	132.0	74.66	0.[illegible]85	4.4
90	45.24	[illegible]	148.5	81.81	0.[illegible]80	2.2
100	50.27	1.68	165.0	87.35	0.[illegible]85	0

TABLE 6. [illegible] PARAMETERS FOR 1966, 345 CID, [illegible]
(2000 rpm - Peak Torque Speed)

Load	Physical Efficiency	Work, kg-m	Torque, ft-lb	Airflow lbs/min	Fuel Flow, lb/min	Manifold Vacuum, in. Hg.
20%	28.9	0.65	44	56.7	0.42	16.9
30%	28.9	0.98	66	69.2	0.51	16.1
40%	30.5	1.35	90	86.1	0.56	14.8
50%	40.2	1.61	110	97.7	0.61	12.6
60%	57.8	1.95	132	104.6	0.62	10.3
70%	67.4	2.25	154	121.5	0.73	6.4
80%	72.1	2.57	176	142.5	0.83	4.3
90%	86.7	2.89	198	154.8	0.97	2.8
100%	96.3	3.21	220	173.2	1.16	0

[redacted]

TABLE 7. CONSTANT VOLUME SAMPLER RESULTS FOR [redacted] ENGINE ON STATIONARY DYNAMOMETER OUTSIDE) USING COMPLETE PROPOSED TEST PROCEDURE—ENGINE RPM 2300 (Peak Torque Speed)

Sample Point	HC (ppm) Grams per 1-HC Test	HC (ppm) Grams per Mile	HC (ppm) Grams per Brake-H Test	CO Grams per 1-HC Test	CO Grams per Mile	CO Grams per Brake-H Test	NOx Grams per 1-HC Test	NOx Grams per Mile	NOx Grams per Brake-H Test
[redacted]									
[redacted]									
[redacted]									

TABLE 8. CONSTANT VOLUME SAMPLER RESULTS FOR 1964 CHEVROLET, 250 CID ENGINE ON STATIONARY DYNAMOMETER CRADLED BEING COMPLETE PROPOSED TEST PROCEDURE—ENGINE RPM 1400

(Peak Torque Speed)

Run No.	B-2b			C			D		
	Grams per Mile Bag	Grams per Test	Grams per Pound of Fuel	Grams per Mile Bag	Grams per Test	Grams per Pound of Fuel	Grams per Mile Bag	Grams per Test	Grams per Pound of Fuel

The Chevy truck results on Table 8 show a more satisfactory mode-to-mode comparison. The fuel consumption data for the Chevy, Table 8, showed a very rapid increase in fuel consumption between 60- and 70-percent power levels and the emissions data confirm this point. Discrepancies in the data at individual power conditions may be a function of the vacuum level in the manifold and whether the load (vacuum level) is increasing or decreasing. The improved repeatability of the modes indicates better engine operation or some improvement in sampling and analysis.

Both Tables 7 and 8 contain bag results taken for all the constant speed power modes from 20 to 100 percent in 10-percent increments. No comparison between the two trucks or between the individual mode data and the composite seems appropriate. Close agreement was obtained using the single composite dilute bag obtained with the CVS system. When using an overall composite bag, the effect of increasing or decreasing load seems to be almost negligible or within the experimental tolerance of this single set of tests. The composite bag is, of course, much simpler and less time consuming and subject to less inaccuracies than the individual mode bag results. This same comment can be offered for the idle and closed throttle results also listed at the bottom of Tables 7 and 8. It is, of course, inappropriate to attempt a comparison of presented experimental data with CVS results using the current Federal procedure.

In brief, some limited experience using the truck version of the constant volume sampler was obtained under a steady-state mapping of engine emissions. During the original IHC engine operation, it was found that at power conditions above 60 percent, the temperatures exceeded 160°F at the inlet to the CVS Roots blower when the system was not allowed to cool between power points. The time between modes was around 10 to 15 min during the initial set of experiments. Later tests were conducted more rapidly with the time reduced to 5 min. Starting at 100-percent load and operation at decreasing power levels was no problem, because the system was at ambient temperature and acted as a heat sink. When operating from the 20- up to 100-percent load conditions, the CVS system increased in temperature beyond the capabilities of the heat exchanger and system in general. To keep the temperature at the inlet to the blower below 145°F, a short CVS cooling period between modes above 60-percent power was found necessary.

Another operational difficulty found during the mode by mode operation with the CVS system was the potentially high rate of NO conversion because of insufficient dilution air to handle the very large exhaust gas volumes at high power settings. The "low speed" or nominal 600-CFM capability of the CVS system pump was employed throughout these studies. Future similar modal operation should employ the "high-speed" 900-CFM CVS truck version flow when necessary to more adequately dilute and "freeze" chemical composition. This is especially necessary for accurate

NO determinations. In summary, it is possible to obtain mode by mode bags of exhaust throughout a power range although the composite bags of a suitable driving cycle would be more desirable.

The continuous NDIR system results are contained in Table 9 for both IHC and Chevy trucks. These concentration values were obtained simultaneously with the CVS data already presented and indicate, in the case of the IHC, much better mode-to-mode repeatability of HC, CO, and NO than that experienced with the CVS bags. On an as-measured concentration basis, this apparent improvement in agreement over CVS may be slightly misleading since the CVS data are presented and compared usually on a brake specific basis.

In general, the concentration values in Table 9 show the Chevy truck to produce more HC and CO for example than the IHC. However, the IHC is a larger displacement engine with more cylinders having higher fuel consumption, air consumption, and power available at the flywheel to do useful work. The grams per 6-min test data listed in Tables 7 and 8 are based on exhaust volume and concentration of contaminants. The indicated differences in emission performance by raw concentration are reversed on this basis. In addition, a much larger difference is indicated, on the order of ten times the HC and six times the CO on a grams per unit of time for the IHC versus the Chevy. One obvious reason for this is the difference in peak torque speeds (2300 rpm for the IHC and 1600 rpm for the Chevy) which result in much more exhaust volume than just the physical size of the two engines would justify. It could be argued that peak torque speed therefore would not be a suitable operating point. Torque, however, is what makes the vehicle move down the road and is still considered a valid engine-vehicle design point and operating condition.

Looking further at the composite CVS bag results at the bottom of Tables 7 and 8, the IHC still produces more HC and CO on a power output or fuel input basis but the magnitude of difference is much less. For example, the HC show about a 4 to 1 difference on a brake specific or fuel basis instead of about 10 to 1 on a grams per unit of time basis. CO exhibits about a 6:1 difference by grams per test and a 3:1 difference on a brake specific basis.

One additional series of experiments was conducted with the IHC truck to determine the emissions in a chassis operated engine instead of a stationary operated engine. Again, emissions were measured by CVS bag and continuous NDIR methods simultaneously. This time, however, the vehicle was operated at various percent loads based on rear wheel power output at peak torque rpm. Rear wheel power output differs from flywheel output due to parasite power losses to fan, air compressor, and power steering, if used, generator, etc. and drive train losses which will vary some depending on load even though operating at a constant rpm.

TABLE 9 CONTINUOUS NDIR SAMPLER RESULTS FOR 1966 IHC, 345 CID AND 1969 CHEVROLET 350 CID ENGINES ON STATIONARY DYNAMOMETER OBTAINED DURING COMPLETE PROPOSED TEST PROCEDURE
(Engine Peak Torque Speed)

Percent* Power	345 CID - IHC (Engine run 4109)			350 CID - Chevrolet (Engine run 4029)		
	HC, PPM Hexane	CO, %	NO, PPM	HC, PPM Hexane	CO, %	NO, PPM
100	180	5.60	917	197	3.95	80
90	80	3.85	1194	140	3.00	80
80	35	1.80	1610	175	5.15	166
70	40	0.45	1801	185	6.60	110
60	40	0.80	1901	138	3.17	70
50	60	0.90	1648	144	1.93	0
40	60	0.70	1363	178	1.75	194
30	60	0.50	1032	195	2.00	385
20	15	0.20	666	170	1.60	500
10	20	0.20	666	168	1.73	335
90	35	0.55	906	*	0.02	230
40	90	0.60	1328	200	1.98	210
50	90	0.80	1574	195	1.80	200
60	45	0.90	1511	180	1.90	180
70	40	0.45	1611	193	0.95	80
80	40	0.70	1668	180	0.90	80
90	75	3.10	1161	180	0.20	40
100	85	4.85	1018	188	0.60	35
Idle	898	10.1	197	178	3.85	167
C.T.	8893	4.6	197	4867	1.96	196

*Observed flywheel hp.

Table 10 describes the pertinent engine operating data for each of the 10-percent power levels. Table 11 contains the observed emissions by the CVS method. It is interesting to compare the CVS chassis results (Table 11) to the test bed results (Table 7) from both an absolute value and a trend basis. Trendwise, the low HC emissions at 70-percent power in Table 7 coincide nicely with the 60-percent power HC in Table 10. No composite hot, idle, or decel emissions were obtained with the chassis tested engine.

Other analyses of the CVS and continuous data have been considered. Based on the preliminary nature of the efforts and the limited number of vehicles, however, it was felt that additional analyses at this time might be premature. The significance of this portion of the study has been to demonstrate (1) some of the test difficulties and advantages in the peak torque mode emissions approach, (2) the variability in results obtainable from two in-service trucks, and (3) the potential of operating on both a chassis or stationary dynamometer. Because of the inherent difficulties of measuring engine power output on chassis machines and because it is the vehicle's engine which produces emissions regardless whether more or less of the power output is expended as parasitic or drive train losses, it would seem that an engine procedure with an alternative chassis procedure which uses the relationship of flywheel power to manifold vacuum as a means for vehicle operation is the most workable and practical. It is uncertain whether 10-percent increments are particularly helpful as additional experiments will be necessary before making a specific recommendation. The idle and closed throttle modes are very important contributors of HC and CO on a concentration basis and should be retained in any new procedure considered. Although the truck version of the constant volume sampler was designed for less strenuous service, improved cooling of the diluted exhaust mixture should permit its operation with the higher power levels contemplated.

F. Relationships Between Brake Specific (CVS) and Concentration (NDIR) Emissions

It is expected that the State of California will issue gaseous emission standards for diesel HC, CO, and NO applicable to new 1973 diesel-powered vehicles. And, it is reported that these standards should be no more difficult or stringent than those already imposed on the heavy-duty gasoline engine, currently 1.5 percent CO and 275 ppm HC. In the course of tests of a number of stationary operated engines under this and other NAPCA contracts, the emissions with the Federal 9-mode cycle were obtained and expressed on a grams/bhp-hr basis.

Using data obtained simultaneously by CVS and continuous NDIR methods, the plots on Figures 28 and 29 for HC and CO, respectively, were made. These relationships are based on data from a total of 11 engines run on either chassis or engine dynamometers under the prescribed 9-mode

TABLE 10. ENGINE PARAMETERS FOR 1966, 345 CID, HIC ENGINE--CHASSIS DYNAMOMETER
(3300 rpm - Peak Torque Speed)

Percent Power	Rear Wheel hp, nhp	Work, hp-hr	Fuel Flow, lb/min	Manifold Vacuum, in. Hg
10	7	0.33	0.386	17.6
20	14	0.47	0.400	15.9
30	21	0.70	0.455	14.1
40	28	0.93	0.513	11.9
50	35	1.17	0.577	10.0
60	42	1.40	0.656	8.0
70	49	1.63	0.702	6.0
80	56	1.87	0.795	4.5
90	63	2.10	0.953	3.4
100	70	2.33	1.087	0

TABLE II. CONSTANT VOLUME SAMPLER RESULTS FOR 1966 IRC. 345 CID ENGINE IN CHASSIS DYNAMOMETER CRADLE DURING THE INDIVIDUAL POWER CONDITIONS—ENGINE RPM 2300 (Peak Torque Speed)

Test Number	HC-Ib			CO			NO		
	Grams per 2-Mile Test	Grams per Mile*	Grams per Pound of Fuel	Grams per 2-Mile Test	Grams per Mile	Grams per Pound of Fuel	Grams per 2-Mile Test	Grams per Mile	Grams per Pound of Fuel

*Based on theoretical mpg of vehicle (power cradle).

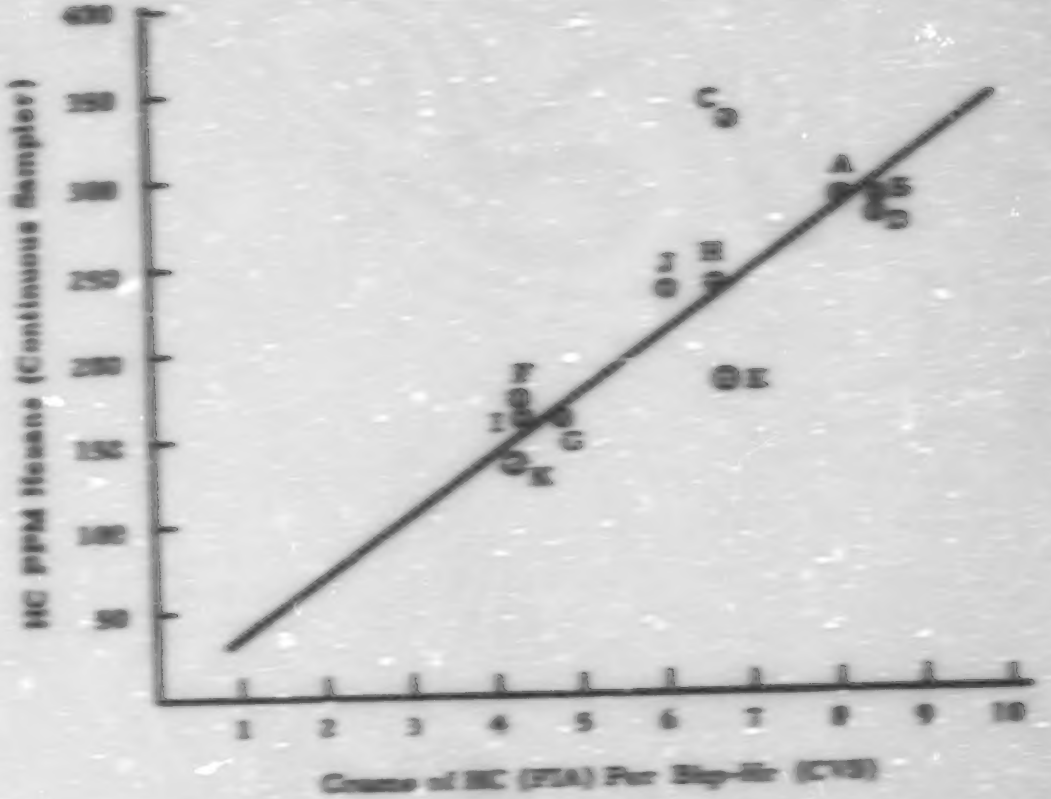

FIGURE 28. COMPARISON OF SIMULTANEOUS RESULTS FOR CONTINUOUS AND CONSTANT VOLUME SAMPLER DURING FEDERAL 9-MODE PROCEDURE

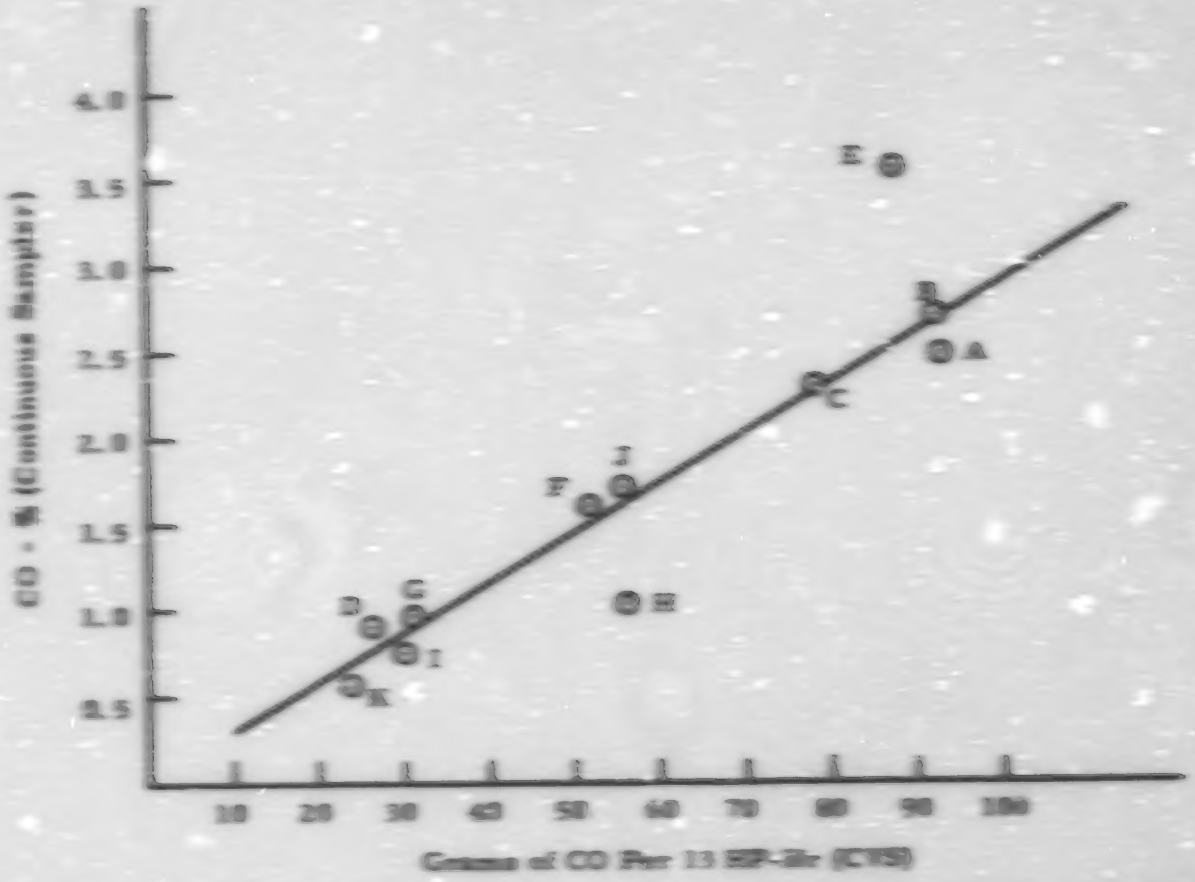

FIGURE 29. COMPARISON OF SIMULTANEOUS RESULTS FOR CONTINUOUS AND CONSTANT VOLUME SAMPLER DURING FEDERAL 9-MODE PROCEDURE

Federal Test (20-min version). The emissions from engines operated on the chassis dynamometer were expressed on a grams/bhp-hr basis by dividing grams/lb of fuel by 0.17, the average ratio between fuel input hp-hr and flywheel hp-hr output based on the six-truck study.

The relationships shown in Figures 28 and 29 are the subjects of continuing interest and are expected to play an increasing role due to the need to express concentration on a brake specific basis. The current 9-mode Federal cycle involves only a few power-producing modes and then several are repeated during the test period. Though only based on a few vehicles and then on a factored brake specific value for some, the relationships appear better than expected. Appendix E contains a list of the engines, their pertinent engine description, and emissions results that form the basis for Figures 28 and 29.

VI. SUMMARY

This report describes the continuing achievements in understanding more about emissions from gasoline-powered vehicles above 6000 GVW. The objective of comparing road emissions of HC, CO, and NO to Federal procedure emissions was accomplished during a study of six trucks of varying size, shape, and use powered by popular but different makes or designs of gasoline engines. As part of the preparations for this study, the truck version of the constant volume sampler was suitably modified for road course emissions sampling. A road route comprising a variety of driving conditions was employed and instrumentation and procedures for recording vehicle parameters of interest were developed. During the six-truck study, chassis dynamometer constant volume and continuous NDIR results were acquired using the current Federally specified 9-mode procedure and the original California cycle. A number of minor revisions to the current Federal cycle were investigated to explore possible improvements in the procedure and their relationship to the road acquired emissions data. Expressing the constant volume results obtained on the chassis dynamometer as grams of contaminate per pound of fuel consumed enabled direct comparisons of chassis dynamometer results with the results obtained on the San Antonio road route.

A preliminary study, employing only two trucks, was made to explore the relationship between engine dynamometer and chassis dynamometer, Federal 9-mode cycle results and to measure emissions over a wider range of engine operation than that in the current Federal method. A number of comparisons resulted between engine-chassis and engine-road results as well as familiarization with a mode type map of emissions at an engine's peak torque speed. Incidental to these studies, an experimentally determined relationship between Federal cycle concentration and mass emissions on a brake specific basis is presented.

VII. CONCLUSIONS AND RECOMMENDATIONS

The following lists the pertinent findings during this year of additional heavy-duty gasoline vehicle emissions research:

(1) The constant volume sampler indicates a better overall CO, NO, and HC agreement between the road and the current Federal procedure than was expected on the basis of previous experimental road-like cycle studies and comparisons. A number of minor modifications to the current Federal test schedule were tried without consistent universal improvement. Cycle modification was found to be highly vehicle/engine dependent, and improvements in one, or sometimes two, emission parameters often resulted in worse agreement in the other one or two emissions.

(2) On the basis of the six-truck study, it appears unlikely that the current Federal cycle can be simply modified to produce emission results that correlate with the road any better than the current Federal procedure. This conclusion is based on using the constant volume sampler, operating a full 20-min procedure, and expressing the results in grams per pound of fuel. The current Federal procedure, however, has some deficiencies. It is not easily expressed on a mass basis in terms of grams per bhp-hr, grams per mile, etc. Also, it does not produce results which can be compared simply with results from other heavy-duty engines such as the diesel.

(3) A comparison of the current Federal cycle and the original California cycle, one of the modifications considered, resulted in gross differences in certain emissions. Based on the continuous NDIR measurements, HC emissions for five of the six trucks were grossly higher (three to four times) when the original California cycle was compared to the current Federal 9-mode procedure while CO emission was lower.

(4) A review of the physical operating data, engine and vehicle speeds, manifold vacuum, and throttle position, indicates the current Federal cycle to be basically an "engine exercise" in that, from the road route rpm traces, 2000 rpm is not really the average speed of operation, if indeed it were meant to be, nor is the highly important constant speed decel realistic, as it represents a long steep closed throttle downhill condition. Rather than acquire the usual single large peak at the beginning of the decel, more typical of nonconstant speed decels, this 45-sec condition is a high HC emitter throughout the period. The six

vehicles rarely operated in a condition which made the engine operate at rated or governed speed. Peak torque engine speed seemed to be more indicative of the majority of operation.

(5) Though the number of vehicles was insufficient to provide a firm conclusion, it seemed that emissions behavior under Federal 9-mode procedure should be roughly equivalent whether stationary or chassis dynamometer operated. Only two vehicles were included in this study, however.

(6) In the limited study of engine modal emissions, it was demonstrated that an engine's emissions could be mapped by using the constant volume sampler to yield mass emissions on a per unit of time, per unit of power output or a per unit of fuel consumed. Though one engine's exhaust may contain a higher concentration of contaminates than another, the grams per unit of time may exhibit the opposite trend--depending on the exhaust volume which depends on an engine's displacement and peak torque speed among other factors. When expressing emissions on a "specific" basis such as per bhp-hr or pound of fuel consumed, some but not necessarily all of the difference in emission rate will be accounted for. It seems that the brake specific basis is the optimum method of expressing heavy-duty vehicle emission rates since engine power output or fuel consumption is usually related to vehicle weight and payload and to a vehicle's duty and worth in transportation.

(7) As a possible alternative to the current Federal procedure, which could be improved by using the constant volume sampler, study of a procedure embodying more power-producing modes at closer spaced intervals is suggested for consideration. Since all trucks and engines do not operate at 2000 rpm as a rule, an engine speed more indicative of the engine's design and operation should be considered such as peak torque speed. The alternative procedure should include enough operating power modes to prevent circumvention of the intent of the procedure yet remain fairly simple and economical to conduct. Idle and closed throttle operation should be included as they are important modes of operation that can produce significant quantities of CO and HC. A self-weighting composite bag via the CVS system would result in a mass emission for the procedure. Direct power output from the stationary engine version could be used to express the emissions on a brake specific basis while the chassis version would depend on the engine's manifold vacuum--flywheel power curve for operation. Such an alternative procedure should permit both chassis and stationary operated engines with their equivalency known. This will allow surveillance and inspection with chassis dynamometers and, if desired, certification and confirmatory tests with vehicles.

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APPENDIX A

METHOD OF COMPUTATION USED TO EXPRESS EMISSIONS ON A MASS BASIS WITH THE CONSTANT VOLUME SAMPLER

CALCULATION METHODS FOR VARIABLE DILUTION SAMPLING SYSTEM

Step 1: Convert temperature chart to an average inlet temperature and record.

Step 2: Using average inlet temperature from chart, determine SCFM and record.

Step 3: Multiply above SCFM times total sample time and record SCF (V_t).

Step 4: Convert meter readings (FIA-CO, CO_2, NO, and HC) to concentration.

Step 5: Subtract background concentration (C_b) from sample concentration (C_s) and enter in column ($C_s - C_b$).

Step 6: Using the number obtained in Step 3, move the decimal point six places to the left and store this number in memory.
Ex: $V_t = 11,827 \times 10^{-6} = 0.011827$.

Step 7: Multiply the number in step five times the number stored in memory from step six. Enter into column $(C_s - C_b) \times V_t$. This applies to all concentrations except CO_2.

Step 8: Multiply the number obtained in Step 7 by the appropriate density and enter in the column total grams.

Step 9: For road data, use substep (a). For all other data, use substep (b).

a. For road data, using the number in Step 8, divide this number by 7.54 and enter the result in the column grams/mile. Then divide this number by 453.6 and enter the result in the column lb/mile. Again using the number obtained in Step 8, divide this number with the weight of fuel for the run and record in the column grams per pound of fuel.

b. For all other data, take the number from Step 8 and divide by the weight of fuel for that run. Enter this number in the column grams per pound of fuel.

DATA SHEET FOR CONSTANT VOLUME SAMPLING SYSTEM

Driver _____ Instrument Operator _____

Run _____ Run No. _____ Date _____ Start _____

Truck No. _____ Start Odo. _____ / _____ CFM _____ Transmission Type _____
Odometer: Start/Stop _____ / _____ SAE _____
Engine Displacement _____ Mfr-type _____ No. of Cyls. _____ No. of Carb. Vents _____

Bar. Pressure, P_b, in. _____ abs _____ corr. Temp _____ / _____ °F
Cold Soaking Time _____ min Total Soak _____
Average Inlet Temp to Sample Pump _____ °F ACFM from Inlet Temp _____

Volume into test sample _____ ACFM Q_p _____ Q_p _____
Volume into background sample _____ ACFM
Weight of Pail _____ V_s = ACFM x Sampling Time _____

Bottle Number	Constituent ID		$CaCO_3$	C_1-C_2 %	Density	Total Grams	Concentration	Volume	Grams/ Gal. of Fuel
	$HCHO_2$	% ppmC							
	$HCHO_3$	% ppmC							
	$HCHO_4$	ppmC							
	$HCHO_5$	ppmC							
	CH_4	ppm							
	CH_4	ppm							
	CH_3OH	%							
	CH_3OH	%							
	NH_3	ppm							
	NH_3	ppm							
	NO_x	ppm							
	NO_x	ppm							

APPENDIX B

EMISSION RESULTS--SIX-TRUCK ROAD ROUTE--CHASSIS DYNAMOMETER STUDY

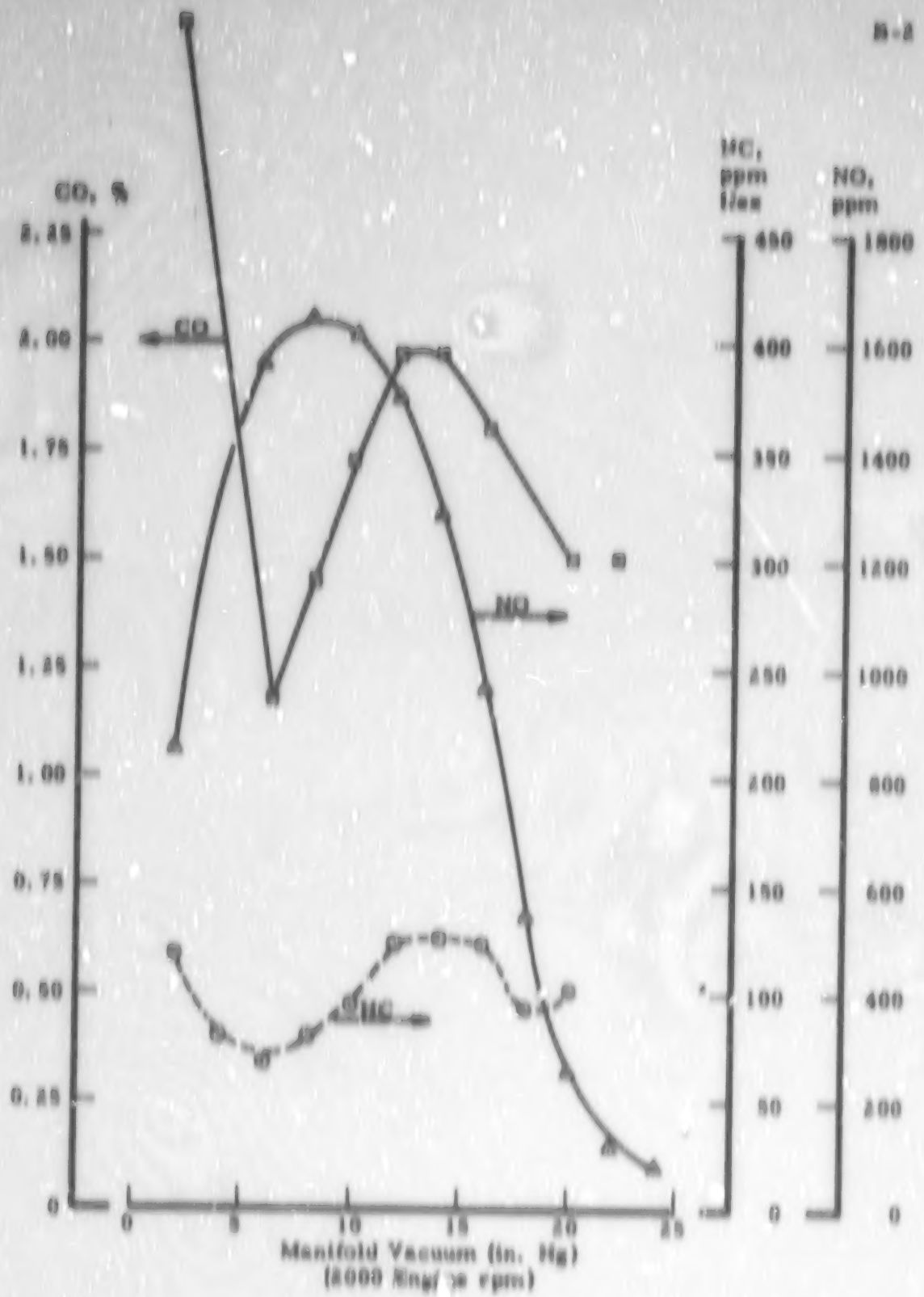

FIGURE B-1. EXHAUST EMISSION CURVE FOR 1966 IHC, 145 CID, 54,000-LB GVW TRUCK

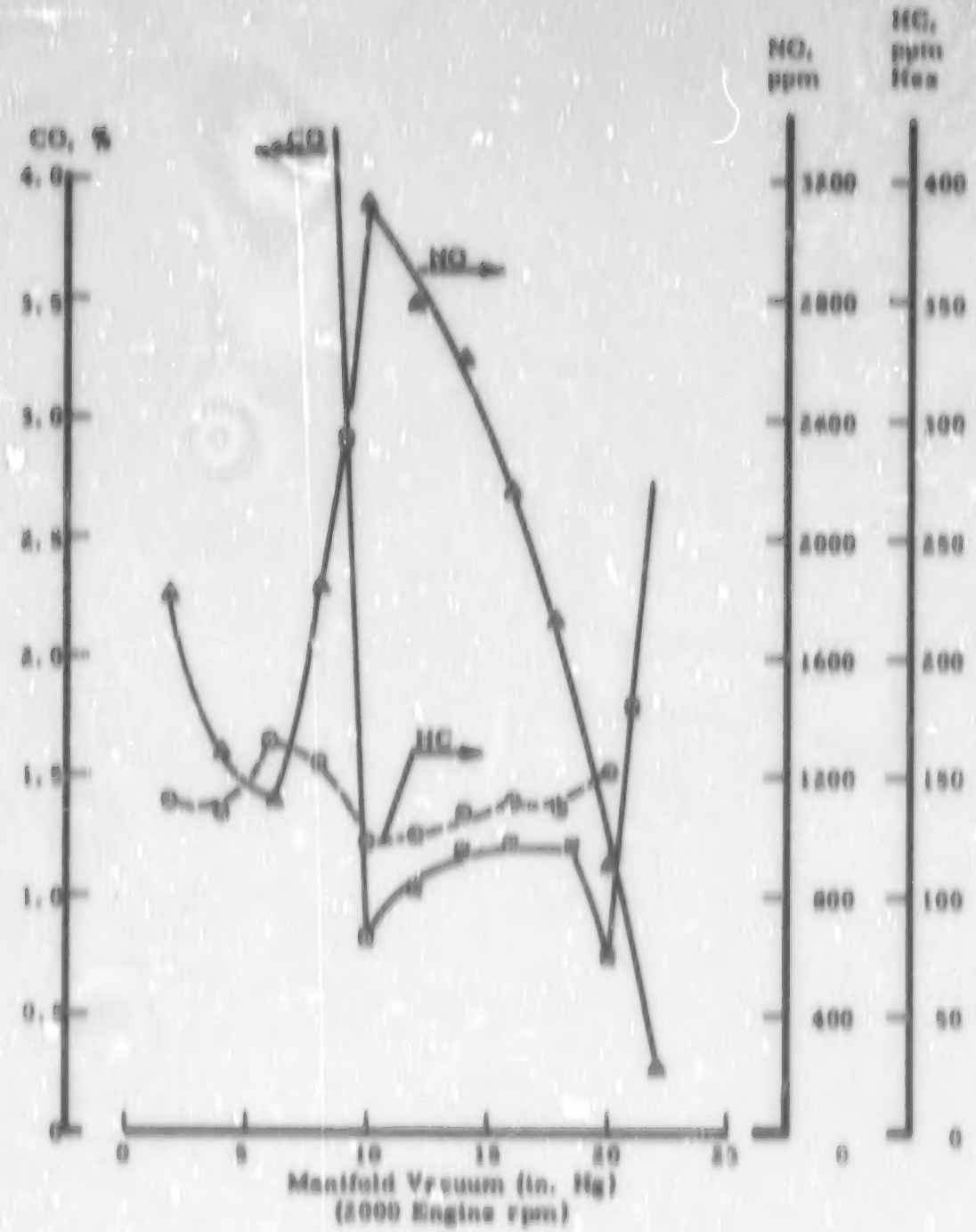

FIGURE B-1. EXHAUST EMISSION CURVE FOR 1968 FORD, 300 CID 17,000-LB GVW TRUCK

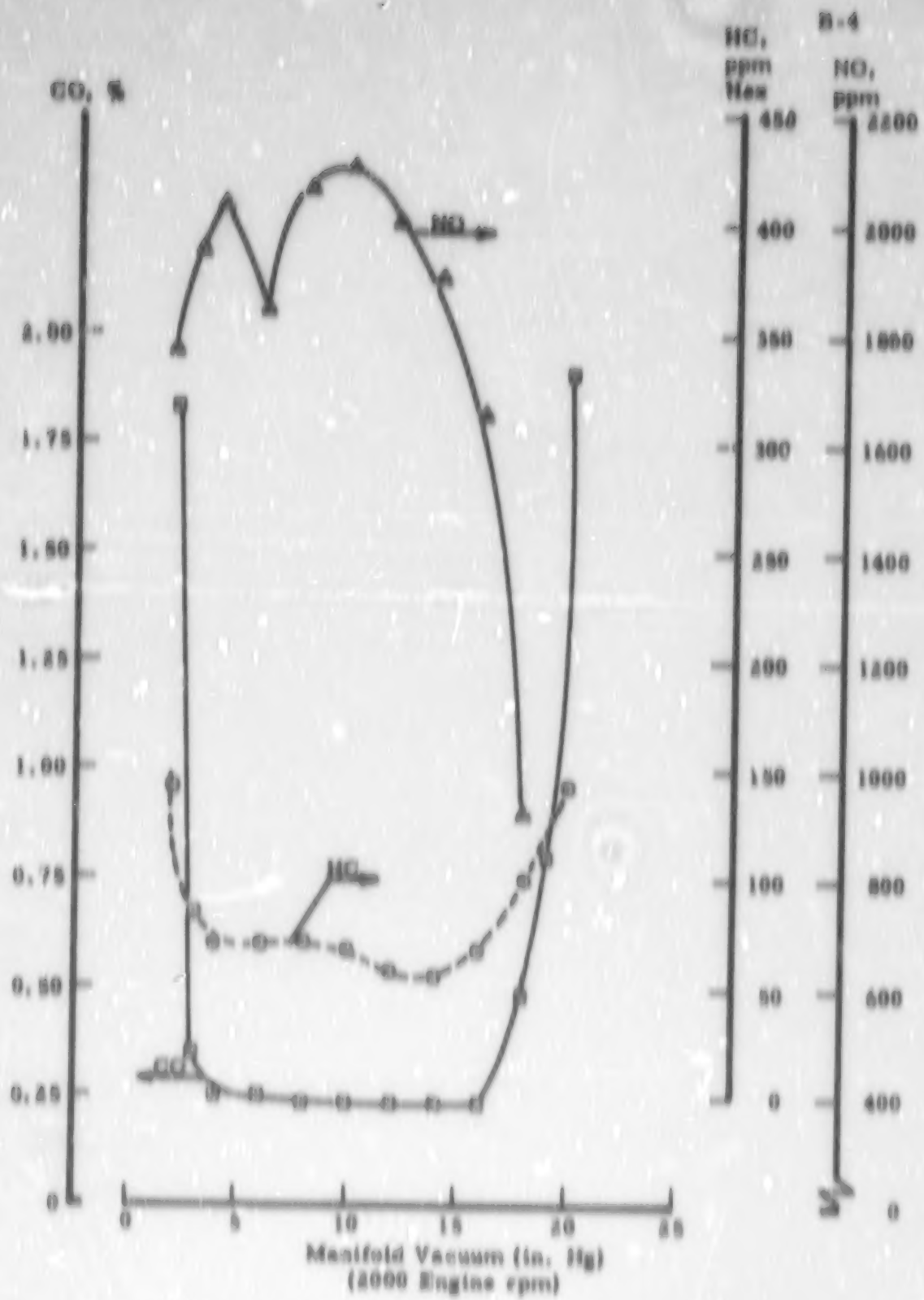

FIGURE B-3. EXHAUST EMISSION CURVE FOR 1969 FORD, 300 CID, 15,000-LB GVW TRUCK

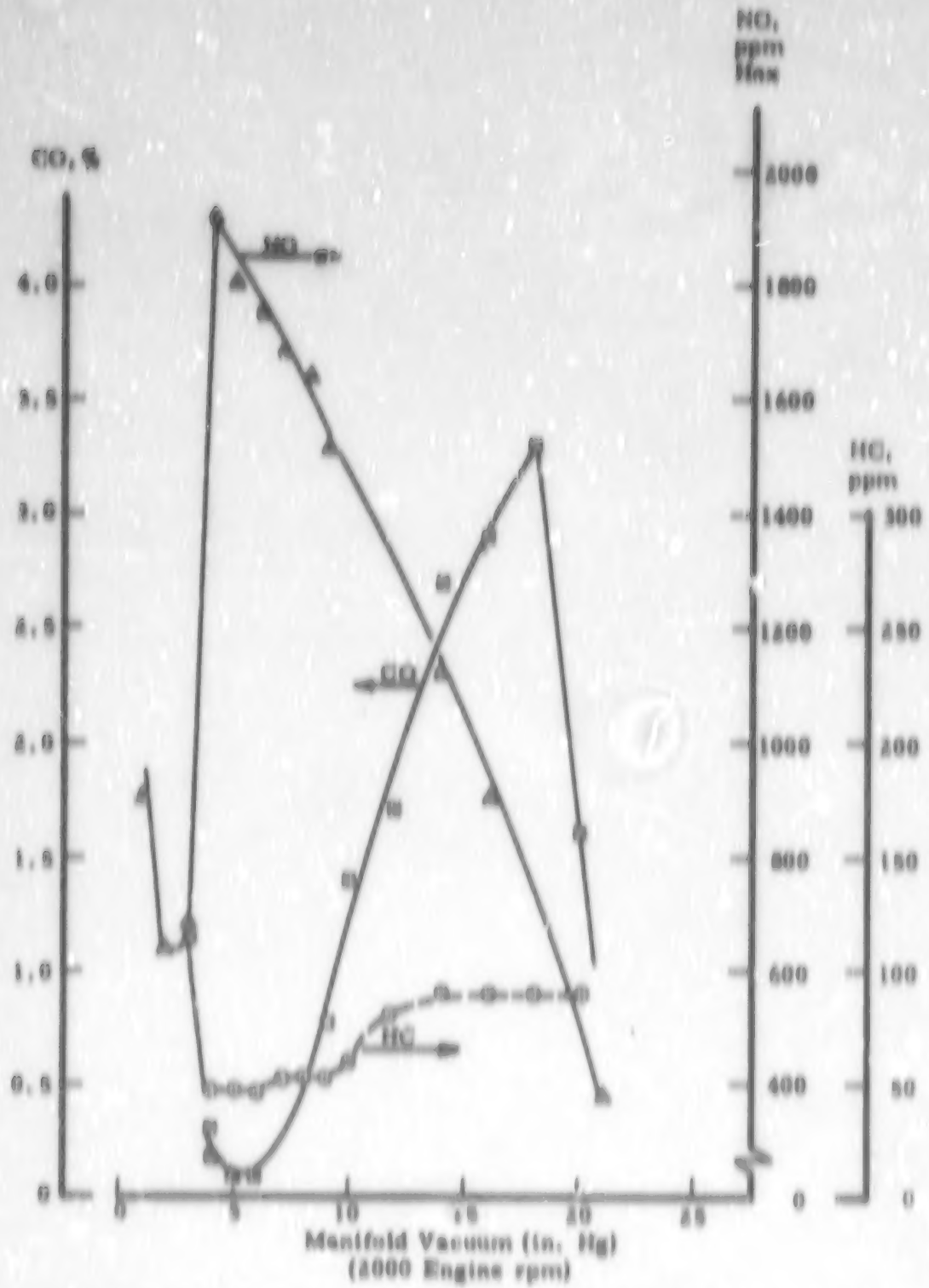

FIGURE B-4. EXHAUST EMISSION CURVE FOR 1969 CHEVROLET, 350 CID, 19,500-LB GVW TRUCK

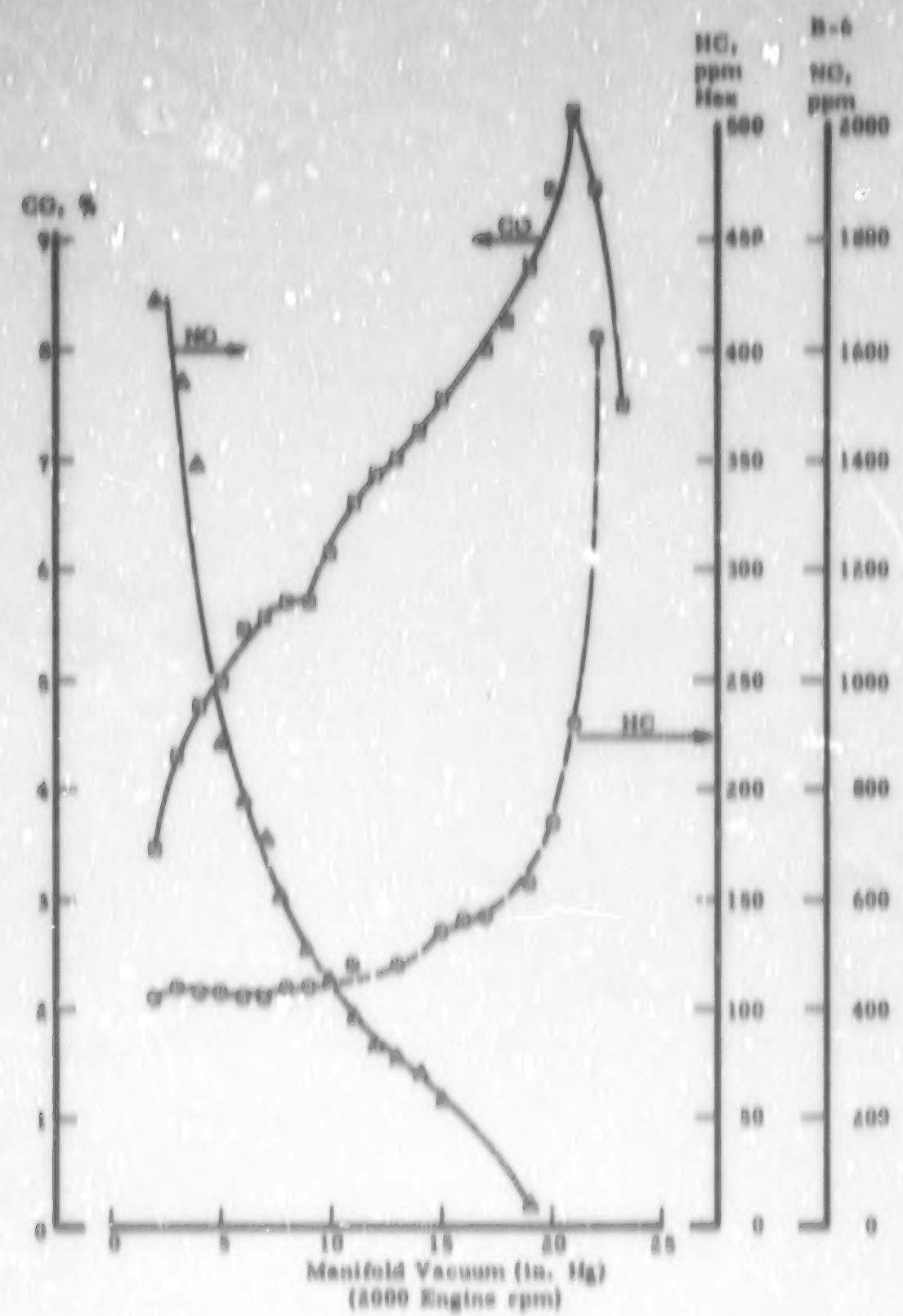

FIGURE B-5. EXHAUST EMISSION CURVE FOR 1968 IHC, 450 CID, 46,000-LB GVW TRACTOR

TABLE B-1. FOUR-CYCLE COMPOSITE FTP RESULTS FOR FEDERAL AND ORIGINAL CALIFORNIA 4-MODE CONSTANT SPEED PROCEDURE (Continuous Sampler)

Vehicle Description					HC Emissions, gpm lbs				Carbon Monoxide, %			
					Federal		California		Federal		California	
Year	Make	CID	GVW	Axle	23 lbs. T	23 lbs. T	23 lbs. T	23 lbs. T	23 lbs. T	23 lbs. T	23 lbs. T	23 lbs. T
1969	Chev	250	10,000	Auto	331	350	975	1046	2.46	2.53	2.53	2.59
					372	388	827	866	4.67	2.66	2.68	2.75
				Avg	376	369	901	956	2.47	2.59	2.61	2.68
1969	IHC	345	14,000	Auto	284	300	1240	1301	2.7	2.8	2.3	2.4
					292	304	1195	1259	2.8	2.9	2.2	2.3
					288	299	1136	1206	3.0	3.1	2.2	2.3
					292	307	1199	1255	2.6	2.7	2.2	2.3
					288	275	—	—	2.3	2.6	—	—
				Avg	377	390	1155	1198	2.7	2.8	2.2	2.3
1969	Ford	330	7,000	Man	337	354	1326	1396	2.5	2.6	1.9	1.9
					324	340	1278	1340	2.4	2.5	1.9	2.0
					340	357	1357	1423	2.3	2.4	1.9	1.9
					331	347	1321	1378	2.3	2.4	1.7	1.8
					288	305	—	—	2.2	2.3	—	—
				Avg	332	349	1370	1437	2.3	2.4	1.9	1.9
1969	Ford	302	15,000	Man	380	396	1584	1645	0.56	0.62	0.42	0.45
					356	370	1411	1470	0.58	0.63	0.39	0.43
					386	398	1589	1647	0.53	0.56	0.41	0.44
					382	392	1549	1592	0.57	0.62	0.46	0.50
					377	392	—	—	0.55	0.59	—	—
				Avg	376	389	1533	1593	0.56	0.59	0.42	0.46
1969	Chev	350	10,000	Man	381	399	1588	1667	3.58	3.72	3.33	3.39
					385	399	1577	1636	3.58	3.72	3.33	3.39
				Avg	379	379	1583	1652	3.58	3.72	3.33	3.39
1969	IHC	407	14,000	Tractor	377	395	1572	1649	1.58	1.65	4.69	4.85
					347	374	1459	1578	1.49	1.75	4.68	5.08
					—	—	1511	1577	—	—	4.69	4.85
				Avg	372	389	1548	1635	1.49	1.65	4.69	4.79

$$\text{HC lbs.} = \frac{26.5}{CO_2 + 0.5\,CO + 13.3\,HC}$$ as specified in the Federal Register, June 4, 1968.

$$\text{CO lbs.} = \frac{26.5}{CO_2 + 0.5\,CO + 13.3\,HC}$$ used with the weighted California test cycle.

TABLE B-2. ROAD AND DYNAMOMETER CONSTANT VOLUME SAMPLER RESULTS
FOR 1968 CHEV. 250 CID, 3d, 000-LB GVW STAKE (Grams per Pound of Fuel)

Method	Date	Hydrocarbons NDIR	Hydrocarbons FIA	CO NDIR	CO_2 NDIR	NO NDIR	Average Fuel mi. /lb.
Road	8-21-69	6.27	12.35	158	956	2.62	4.64
	8-21-69	7.46	13.95	197	1195	3.23	3.81
	8-21-69	6.67	12.46	153	1175	3.77	4.13
	8-21-69	6.89	13.48	168	1261	4.15	4.06
	8-21-69	6.81	13.56	148	1263	4.69	4.01
	8-21-69	6.55	13.59	138	1181	4.26	3.97
	Avg	7.11	13.16	197	1219	4.02	4.32
Federal	8-18-69	8.22	13.69	135	1085	N.D.	3.97
	8-18-69	7.61	12.11	120	961	N.D.	4.07
	8-18-69	6.88	11.75	104	1001	5.33	4.07
	8-19-69	7.89	12.85	133	1089	4.62	4.08
	8-19-69	7.52	11.36	129	1248	5.79	4.26
	8-19-69	7.69	11.62	138	1299	5.30	4.12
	Avg	7.80	14.79	134	1110	5.33	4.08
California	8-19-69	18.85	15.37	123	1196	5.39	4.09
	8-19-69	9.65	15.41	121	1209	5.39	4.06
	8-19-69	10.3x	16.33	135	1206	5.37	4.06
	Avg	9.93	15.67	133	1163	5.36	4.06
Modification No. 1	8-22-69	7.53	12.19	139	1259	4.79	3.78
20 to 30 m. (Mode 3)	8-27-69	7.88	12.46	153	1271	3.23	3.79
	Avg	7.25	12.39	146	1156	4.01	3.79
Modification No. 2	8-22-69	6.56	12.67	94	1403	N.D.	3.92
3 to 5 m. (Mode 7)	8-22-69	6.79	11.96	91	1256	N.D.	3.91
	Avg	6.67	12.32	93	1327	—	3.92
Modification No. 3	8-25-69	8.79	14.62	131	1190	2.6	3.92
20 to 30 m. (Mode 3)	8-25-69	3.93	13.66	107	1026	5.19	3.93
and 3 to 5 m. (Mode 7)	8-25-69	7.84	15.57	104	1021	4.37	3.69
	Avg	6.85	14.62	114	1079	4.05	3.85

TABLE B-3. ROAD AND DYNAMOMETER CONSTANT VOLUME SAMPLER RESULTS FOR 1966 DIC, 345 CID, 24,000-LB GVW STAKE (Grams per Pound of Fuel)

Method	Date	Hydrocarbons NDIR	Hydrocarbons FID	CO NDIR	CO_2 NDIR	NO NDIR	Average Fuel Mpg
Run*	9-17-69	6.18	10.16	118	1617	4.70	6.13
	9-17-69	6.46	11.19	98	1969	6.11	8.57
	9-17-69	6.06	10.21	89	1134	3.31	6.56
	9-17-69	6.06	10.07	99	1161	3.60	6.11
	9-17-69	6.73	11.14	87	1910	N.D.	8.75
	Avg	6.70	10.55	98	1117	3.88	8.38
Federal	9-15-69	5.46	10.01	132	1019	3.68	6
	9-15-69	5.42	10.06	131	1117	3.17	6
	9-15-69	6.65	11.10	145	1108	3.76	6
	9-15-69	5.48	11.14	134	908	3.46	6
	9-16-69	6.26	12.58	135	1109	3.84	6
	Avg	5.89	12.50	135	1052	3.49	6
California	9-15-69	10.65	18.94	124	1154	4.06	5.76
	9-15-69	10.12	17.67	127	1215	4.29	5.81
	9-15-69	10.25	18.78	124	1241	4.25	5.69
	9-16-69	10.20	19.08	125	1064	3.36	5.88
	Avg	10.30	18.61	125	1218	3.98	5.81
Modification No. 1 10 to 10 in. (Mode 8)	9-18-69	7.14	11.15	127	1171	2.60	5.24
	9-18-69	6.87	11.18	134	1175	2.80	5.22
	9-18-69	7.07	12.64	135	1170	2.80	5.23
	Avg	7.04	11.19	132	1172	2.61	5.23
Modification No. 2 5 to 5 in. (Mode 7)	9-18-69	5.43	10.83	87	1196	3.36	5.60
	9-18-69	5.58	11.80	90	1268	2.67	5.86
	Avg	5.51	11.32	89	1232	3.01	5.51
Modification No. 3 5 to 9 in. (Mode 7)	9-19-69	6.11	11.79	98	1141	3.72	5.36
	9-22-69	5.81	12.08	97	1255	3.11	5.39
	Avg	5.96	11.92	96	1198	2.98	5.38
Modification No. 4 10 to 9 in. (Modes 6 and 8)	9-22-69	5.20	11.67	118	1157	3.65	6.57
	9-22-69	5.47	9.67	121	1207	3.63	6.55
	Avg	5.34	10.69	120	1180	3.61	6.56
Modification No. 5 (One Run) 10 to 10 in. (Modes 6 and 8)	9-23-69	5.01	10.74	132	1137	5.42	6.61
Modification No. 6 10 to 10 in. (Mode 8)	9-23-69	5.76	9.67	117	1080	4.69	6.59
	9-23-69	5.45	10.44	118	1098	3.76	6.61
	Avg	5.61	9.86	118	1099	5.71	6.24

TABLE B-4. ROAD AND DYNAMOMETER CONSTANT VOLUME SAMPLER RESULTS FOR 1968 FORD, 330 CID, 17,000-LB GVW VAN (Grams per Pound of Fuel)

Method	Date	Hydrocarbons NDIR	Hydrocarbons FID	CO NDIR	CO_2 NDIR	NO NDIR	Average Fuel mi./lb.
Road	10-10-69	8.54	15.96	154	1019	3.64	6.66
	10-10-69	11.07	19.11	174	1086	4.63	6.38
	10-10-69	10.65	21.04	194	1160	4.96	6.15
	10-10-69	9.43	17.01	161	1007	4.04	6.35
	10-10-69	8.94	17.99	16.51	971	3.38	6.10
	Avg	9.68	18.14	171	1051	4.04	6.33
Federal (6 idle)	10-1-69	6.19	11.69	101	1108	5.43	6.01
	10-1-69	5.86	10.13	110	1115	6.29	6.33
	10-1-69	6.11	9.77	118	1101	6.17	6.18
	10-1-69	6.11	9.98	121	1103	6.23	6.20
	10-1-69	6.15	10.43	116	1113	5.93	6.20
	Avg	6.09	10.33	119	1128	6.14	6.14
Alternate Federal (6 idle)	10-2-69	6.80	12.01	100	1037	5.31	6.03
	10-2-69	5.93	10.96	122	1135	6.66	6.17
	10-2-69	5.87	11.39	114	1050	6.42	6.12
	10-2-69	5.90	11.98	120	1092	6.29	6.08
	10-2-69	5.97	11.72	114	1048	5.96	6.10
	Avg	6.10	12.41	119	1070	5.92	6.14
California	10-3-69	11.62	17.70	109	1158	6.06	6.31
	10-3-69	8.95	17.86	95	1114	6.09	6.46
	10-3-69	9.56	16.67	93	1077	7.61	6.25
	10-3-69	10.01	17.56	96	1151	6.00	6.13
	10-3-69	9.43	18.35	98	1135	6.97	6.23
	Avg	9.81	17.58	98	1139	6.74	6.28
Modification No. 1 10 to 19 in. (Mode 6)	10-14-69	8.19	13.01	110	1101	3.50	6.90
	10-14-69	6.41	13.01	144	1076	6.21	6.07
	10-14-69	6.23	12.73	126	1065	6.50	6.86
	Avg	6.28	13.18	121	1074	6.10	6.87
Modification No. 2 3 to 9 in. (Mode 7)	10-16-69	8.84	11.17	101	1064	7.60	6.61
	10-16-69	8.19	11.91	101	1067	7.61	6.35
	10-16-69	8.14	11.69	100	1105	7.60	6.43
	Avg	8.05	11.69	101	1106	7.87	6.51
Modification No. 3 10 to 2 in. (Mode 5)	10-15-69	8.00	15.05	110	1006	8.61	7.00
	10-15-69	8.88	16.57	119	1036	8.19	7.16
	Avg	8.44	15.81	115	1021	8.81	7.08
Modification No. 4 10 to 3 in. (Mode 5)	10-15-69	8.87	9.87	110	1105	8.68	7.20
Modification No. 5 15 to 17 (Mode 8)	10-15-69	8.11	14.87	108	1017	7.78	6.99
Modification No. 6 Idle 30 sec; 15 in. (Mode 8) 61 sec	10-15-69	5.41	9.76	100	1174	7.66	7.16

TABLE B-5. ROAD AND DYNAMOMETER CONSTANT VOLUME SAMPLER RESULTS FOR 1969 FORD, 300CID, 10,000-LB GVW VAN (Grams per Pound of Fuel)

Method	Date	Hydrocarbons NMHC	Hydrocarbons FID	CO HDHC	CO_2 HDHC	NO HDHC	Average Fuel mi/lb
Road	10-08-69	5.45	11.10	104	1401	5.13	5.05
	10-10-69	5.81	11.10	115	1411	4.81	5.06
	10-10-69	5.68	11.48	108	1398	5.09	5.03
	Avg	5.65	11.23	109	1321	5.28	5.06
Federal	10-15-69	5.89	10.58	N.D.	1261	7.65	6.66
	10-22-69	6.92	14.07	55	1266	8.45	6.67
	10-22-69	7.91	15.06	65	1157	9.16	6.36
	10-22-69	7.50	15.01	62	1259	8.10	6.66
	11-12-69	7.58	14.96	61	1250	8.95	6.61
	Avg	7.27	14.07	60	1227	8.45	6.62
Alternate Federal	10-21-69	7.11	13.00	58	1156	7.66	6.68
	10-23-69	6.66	12.53	50	1182	9.12	6.17
	10-23-69	7.12	12.05	50	1156	8.91	6.27
	10-23-69	6.81	12.27	57	N.D.	9.68	6.19
	Avg	6.93	12.69	59	1164	8.81	6.23
California	10-24-69	9.50	20.61	55	1330	10.66	6.61
	10-24-69	9.77	21.29	57	1250	10.15	6.59
	10-24-69	9.51	20.66	56	1324	8.61	6.63
	10-24-69	9.53	N.D.	63	1348	9.34	6.61
	Avg	9.60	20.79	56	1318	9.51	6.46
Modification No. 1 10 to 19 in. (Mode 5)	10-28-69	7.06	15.01	68	1210	7.68	5.90
	10-29-69	7.81	16.10	65	1274	7.98	5.96
	10-29-69	7.06	14.68	58	1318	7.35	5.79
	Avg	7.30	14.96	66	1267	7.68	5.88
Modification No. 2 1 to 9 in. (Mode 7)	10-21-69	5.26	9.79	52	1208	7.69	6.16
	10-29-69	5.76	9.10	50	1366	6.68	6.21
	10-29-69	5.05	7.92	36	1416	N.D.	6.19
	10-29-69	6.06	10.12	56	1258	8.16	6.06
	10-28-69	5.16	8.76	48	1357	8.83	6.08
	Avg	5.20	9.11	50	1356	8.81	6.11
Modification No. 3 10 to 0 in. (Mode 8)	10-31-69	5.69	10.28	60	1358	9.81	6.68
	10-31-69	7.00	12.87	62	1296	10.71	6.10
	11-3-69	6.72	11.10	55	1238	8.86	6.58
	11-3-69	6.85	10.78	60	1400	9.82	6.66
	Avg	6.94	11.71	59	1373	9.18	6.61
Modification No. 4 10 to 9 in. (Mode 9)	11-3-69	5.56	10.39	58	1333	8.68	5.15
	11-3-69	6.06	10.53	58	1483	8.59	5.05
	Avg	5.86	10.46	58	1407	8.51	5.10
Modification No. 5 19 to 0 in (Mode 8)	11-3-69	9.21	15.55	83	1303	9.11	6.29
	11-3-69	9.60	17.31	66	1338	10.12	6.15
	11-4-69	8.86	21.91	88	1309	8.88	6.23
	Avg	9.16	18.39	65	1381	9.56	6.19
Modification No. 6 30 sec Idle, 85 sec 19 in. (Mode 6)	11-4-69	8.17	8.01	46	1612	10.18	6.06
	11-4-69	8.68	7.68	48	1608	10.12	6.03
	Avg	8.28	7.84	46	1609	10.15	6.05

TABLE B-6. ROAD AND DYNAMOMETER CONSTANT VOLUME SAMPLER RESULTS
FOR 1966 CHEV, 350 CID, 10,500-LB GVW VAN (Grams per Pound of Fuel)

Method	Date	Hydrocarbons NDIR	Hydrocarbons FID	CO NDIR	CO_2 NDIR	NO NDIR	Average Fuel mi/gal
Road	12-1-69	5.63	9.67	188	1193	3.37	7.41
	12-1-69	5.85	9.83	150	1056	3.27	7.25
	12-1-69	5.66	9.86	167	115[illegible]	3.09	7.46
	Avg	5.72	9.79	171	1088	3.24	7.51
Federal	11-25-69	6.65	10.11	120	1135	2.66	7.02
	11-25-69	6.12	9.75	130	956	2.61	6.98
	11-25-69	6.88	9.65	132	952	2.66	6.85
	11-25-69	7.12	10.40	136	962	2.60	6.99
	Avg	6.64	9.98	129	1011	2.62	6.96
California	11-25-69	6.74	10.75	126	949	3.62	6.66
	11-25-69	7.28	11.57	123	1121	3.71	6.54
	11-25-69	6.75	11.27	118	1094	3.62	6.69
	11-25-69	6.26	10.36	143	1181	4.03	6.63
	Avg	6.76	11.14	125	1086	3.75	6.63
Modification No. 1	11-25-69	7.48	10.96	152	1151	2.84	6.88
18 to 19 in. (Mode 3)	11-25-69	7.76	10.59	150	1122	2.82	6.88
	Avg	7.62	10.78	151	1127	2.83	6.86
Modification No. 2	11-25-69	6.68	10.41	73	1304	4.98	6.25
3 to 5 in. (Mode 7)	11-25-69	6.52	9.08	72	1296	4.44	6.21
	Avg	6.70	9.75	72	1299	4.71	6.18
18 to 6 in. (Mode 3)	12-2-69	5.67	7.25	129	1067	4.76	7.0
18 to 9 in. (Mode 3)	12-2-69	5.73	9.16	194	1834	2.36	7.39
	12-2-69	5.25	8.07	189	1895	2.72	7.38
	Avg	5.49	8.62	192	1865	2.74	7.34
16 to CT (Mode 8)	12-2-69	8.38	12.07	136	1871	3.48	6.28

TABLE 3-7. ROAD AND DYNAMOMETER CONSTANT VOLUME SAMPLER RESULTS FOR 1969 IHC, 450 CID, 26,000-LB GVW TRACTOR (Grams per Pound of Fuel)

Method	Date	Hydrocarbons NDIR	Hydrocarbons FIA	CO NCDR	CO_2 NDIR	NO NDIR	Average Fuel wt, lb
Road	12-11-69	6.23	12.27	129	1165	4.68	8.72
	12-11-69	6.14	10.61	125	1076	4.73	8.53
	12-11-69	6.12	12.25	127	940	4.41	8.68
	Avg	6.16	11.71	127	1060	4.61	8.64
Federal	12-15-69	5.17	7.89	80	1247	5.93	9.28
	12-15-69	4.42	6.46	81	1092	5.85	9.21
	Avg	4.80	6.78	81	1170	5.69	9.21
California	12-19-69	4.36	8.35	191	678	2.57	10.14
	12-19-69	4.23	8.18	195	633	2.70	10.11
	12-19-69	4.37	N.D.	195	718	2.77	10.32
	Avg	5.95	8.27	194	81.	2.68	10.16
Modification No. 1	12-22-69	5.40	9.08	178	895	3.39	8.98
18 to 19 in. (Mode 3)	12-22-69	5.39	9.38	181	805	3.35	9.05
	Avg	5.40	9.23	180	840	3.37	9.02
Modification No. 2	12-22-69	4.12	7.11	297	765	2.59	10.53
3 to 5 in. (Mode 7)	12-22-69	3.98	7.61	279	777	2.63	10.42
	Avg	4.05	7.36	288	771	2.61	10.48
Modification No. 3	12-22-69	3.70	6.81	267	746	3.24	11.13
10 to 6 in. (Mode 3)							

APPENDIX C

EMISSION RESULTS--1-TRUCK CHASSIS--ENGINE DYNAMOMETER STUDY (FEDERAL 9-MODE CYCLE)

TABLE C-1. CONSTANT VOLUME AND CONTINUOUS SAMPLER RESULTS FOR 9-MODE FEDERAL TRUCK CYCLE FOR 1966 IHC, 345 CID, 24,000-GVW STAKE TRUCK

		Continuous Sampler			Constant Volume Sampler (grams per pound of fuel)			
Date	Dynamometer	Hydrocarbons, PPM - Hexane	CO, %	NO, PPM	Hydrocarbons, FIA	CO	NO	Fuel Weight, lb
5-15-70	Stationary	272	1.78	1479	11.48	80	*	6.85
5-15-70	Stationary	252	1.67	1385	11.05	80	*	6.99
5-15-70	Stationary	280	1.73	1326	11.39	82	*	6.85
	Average	268	1.73	1363	11.27	81	*	6.86
5-6-70	Chassis	286	2.39	934	10.48	94	2.52	6.17
5-6-70	Chassis	305	2.66	895	10.69	93	3.06	6.12
5-6-70	Chassis	306	2.69	860	11.45	99	3.33	6.14
	Average	298	2.58	863	10.89	95	2.96	6.14
6-15-70	Chassis	285	2.39	1266	10.33	100	2.86	6.99
6-15-70	Chassis	282	2.26	1316	10.38	105	3.12	6.94
	Average	284	2.33	1291	10.35	107	2.99	6.97
	Chassis Average	290	2.46	1077	10.62	101	2.98	6.55
	Stationary Average	268	1.73	1363	11.27	81	*	6.86

*No data.

TABLE C-2. CONSTANT VOLUME SAMPLER RESULTS FOR 6-MODE FEDERAL CYCLE FOR 1969 CHEVROLET, 250 CID, 10,000-GVW STAKE TRUCK

		California Sampler			Constant Volume Sampler (grams per pound of fuel)			
Date	Transmission	Hydrocarbons, PPM Hexane	CO, %	NO, PPM	Hydrocarbons, PPM	CO	NO	Fuel Weight, lb
6-25-70	Engine	260	3.85	1951	14.57	374	3.51	4.72
6-25-70	Engine	240	3.99	1559	13.16	385	3.47	4.67
6-25-70	Engine	255	3.96	1682	14.85	383	4.10	4.79
	Average	256	3.93	1664	13.85	380	3.72	4.79
6-26-70	Engine	265	3.99	1950	8.96	286	4.03	4.69
6-26-70	Engine	246	4.01	2525	9.57	281	3.66	4.69
6-26-70	Engine	248	4.26	1542	10.39	289	3.61	4.76
	Average	253	4.42	1685	9.65	290	3.77	4.71
6-18-70	Chevelle	282	3.37	1273	7.60	341	4.56	4.75
6-18-70	Chevelle	194	4.24	1318	7.75	365	4.90	4.70
6-18-70	Chevelle	208	3.70	1320	8.05	346	4.52	4.79
	Average	281	3.77	1369	7.80	457	4.65	4.73
5-12-70	Chevelle	236	3.96	1650	8.95	377	2.30	4.66
5-12-70	Chevelle	232	4.05	1817	10.32	378	1.75	4.64
	Average	223	3.99	1823	9.56	378	2.03	4.65
	Chevelle Average	232	3.88	1562	8.99	360	3.36	4.69
	Engine Average	253	3.47	1525	11.7[illegible]	330	3.75	4.73

APPENDIX D

EMISSION RESULTS--A-TRUCK ENGINE--CHASSIS STUDY (PEAK TORQUE POWER MODES)

TABLE D-1. CVS COMPOSITE POWER MODE RESULTS FOR 1966 IHC AND 1969 CHEVROLET AT PEAK TORQUE ENGINE SPEED (Stationary Operated)

1966 IHC, 345 CID
(2,500 rpm)

Condition	Nonmethane n-Pb			Carbon Monoxide			Nitrogen Oxide		
	Grams per 2-Mile Test	Grams per Mile/hr.	Grams per Pound of Fuel	Grams per 2-Mile Test	Grams per Mile/hr.	Grams per Pound of Fuel	Grams per 2-Mile Test	Grams per Mile/hr.	Grams per Pound of Fuel
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Average	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Average	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

1969 Corvette, 350 CID
(2,600 rpm)

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Average	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Average	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

TABLE D-2. CVS AND CONTINUOUS RESULTS FOR THE IDLE AND CLOSED THROTTLE MODES FOR THE 1964 BIC-345 CID AND THE 1969 CHEVROLET-250 CID

1964 BIC. 345 CID

Condition	Engine rpm	Constant Volume Sampler: Hydrocarbons - ppm Grams per 3-Mile Test	Hydrocarbons - ppm Grams per Pound of Fuel	CO Grams per 3-Mile Test	CO Grams per Pound of Fuel	NO Grams per 3-Mile Test	NO Grams per Pound of Fuel	Continuous Sampler: Hydrocarbons, PPM Hexane	CO, %	NO, PPM
Idle	600	5.55	28.7	46.3	240	0	0	870	10.4	110
Idle	600	6.32	32.8	51.6	267	0	0	920	9.9	140
Idle	600	6.87	32.5	47.8	226	0	0	985	9.9	156
Average		5.92	31.7	48.2	244	0	0	858	10.1	157
Closed Throttle	2300	6.89	27.2	31.3	148	0	0	1400	2.8	110
Closed Throttle	2300	7.32	32.1	34.9	153	0	0	2350	2.1	140
Closed Throttle	2300	6.88	27.2	32.5	145	0	0	2850	2.2	156
Average		6.42	28.9	46.4	132	0	0	2233	2.4	157

1969 Chevrolet, 250 CID

Idle	550	6.75	7.65	36.1	256	0	0	375	5.1	330
Idle	550	6.55	5.85	36.2	257	0	0	375	2.8	385
Idle	550	6.64	6.89	36.7	260	0	0	370	2.6	385
Average		6.65	6.80	36.4	259	0	0	373	5.2	367
Closed Throttle	1600	10.36	60	31.0	220	0	0	4650	1.1	258
Closed Throttle	1600	13.76	156	34.6	245	0	0	4650	1.1	315
Closed Throttle	1600	13.31	130	34.5	245	0	0	5300	1.1	257
Average		12.36	121	34.9	247	0	0	4867	1.1	256

APPENDIX B

EMISSION RESULTS--BRAKE SPECIFIC AND CONCENTRATION STUDY (FEDERAL 9-MODE CYCLE)

TABLE E-1. EMISSION RESULTS FOR SIMULTANEOUS CONTINUOUS AND CONSTANT VOLUME SAMPLING (FEDERAL 9-MODE PROCEDURE)

			Continuous		CVS	
Code*	C.I.	No. of Cylinders	Volume	CO, %	HC, grams per bhp-hr	CO, grams per bhp-hr
A	250	I-6	276	2.47	8.17	93.19
B	345	V-8	277	2.78	8.55	92.39
C	330	V-8	332	2.39	6.82	78.67
D	300	V-8	274	0.84	8.57	26.41
E	350	V-8	178	3.58	6.79	87.79
F	450	V-8	172	1.68	4.58	58.72
G	292	I-6	158	8.96	4.88	30.80
H	360	V-8	239	1.84	6.63	56.44
I	302	V-8	161	4.76	4.36	29.68
J	318	V-8	234	1.73	6.06	55.93
K	400	I-6	136	8.53	4.29	23.86

*Year engine manufactured
5 - 1970 Engines
2 - 1969 Engines
3 - 1968 Engines
1 - 1966 Engines.